TAFE NSW

UEEEC0064
Solve oscillator problems

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Learner Resource

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Oscillators

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The Electronics Section
Ultimo Campus of TAFE NSW
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Introduction

This workbook has been written to help students satisfy the assessment requirements for the following Unit:

- UEEEC0064 - Solve oscillator problems

More information about electrotechnology training packages and the above Units can be found at www.training.gov.au/home/tga. Type the course/unit number in the "Quick search" and press return.

Lesson organiser

Lesson	Section	Topics and activities
Before starting (ideally)	Required reading	■ Workplace Health & Safety ■ Using sustainable energy practices ■ Communication and documentation ■ Making measurements and isolating circuits
1	1	■ What is an oscillator and oscillator applications ■ Positive feedback and Barhkausen's Criteria for oscillation ■ Generic fault-finding techniques for oscillator circuits ■ Develop an advanced understanding of function generator operation
2	2	■ The RC phase shift oscillator ■ The Wien-brdige oscillator ■ Fault-finding phase shift oscillators ■ Practise measuring key voltages in a phase shift oscillator (the Wien-bridge oscillator) using an oscilloscope
3	3	■ The Hartley oscillator ■ The Colpitts oscillator ■ The Modified Colpitts (or Clapp) oscillator ■ Isolation the LC feedback network from the supply rail ■ Practise measuring key voltages in LC oscillators using an oscilloscope
4	4	■ Quartz crystals and crystal-controlled oscillators ■ Fault-finding BJT oscillators ■ Voltage-controlled oscillators (sinusoidal) ■ Verifying the operation of an integrated circuit VCO using a DMM and an oscilloscope
5	5	■ The Pierce oscillator and fault-finding ■ RC relaxation oscillators (including the NE555 Timer astable multivibrator) and fault-finding ■ Voltage-controlled oscillators (digital) ■ Practise measuring key voltages in digital oscillator circuits using an oscilloscope
6	■ **Assessments - Refer to UAG for details**	

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Student notes

Required reading

Purpose These notes are provided to support your revision on aspects of this Unit that have been taught before in other Units (typically more than once) and will not be taught again but may be assessed.

This issue is explained in more detail on the following pages.

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Introduction

As you probably know, *units of competence* that make up qualifications in the Electrotechnology Training Package (like CIII Electronics and Communications) prescribe what must be taught and assessed.

This is done using *elements of competence* together with *performance criteria* for each element. More detail on these is provided in the *assessment requirements* for the unit using two lists: one is the list of *performance evidence*; and the other is the list of *knowledge evidence*.

There are some performance criteria (together with performance evidence and/or knowledge evidence in the assessment requirements) that appear in many units and these include items on the following topics:

- work health and safety (WHS)
- using sustainable energy practices
- the appropriate use and completion of documentation
- appropriate communication with supervisors, customers and other stakeholders.

It makes sense that these performance criteria are common to multiple units because, taking WHS as an example, it's not reasonable to claim competence when the work was completed successfully but in an unsafe way.

Importantly, where all these topics have been comprehensively taught before, it is usually unnecessary to teach them a second or third time. That said, we are still expected to ask you to provide knowledge evidence and/or performance evidence possibly by answering questions on these topics in the theory test and/or demonstrating your skills on these topics during the practical tests.

For this reason, the following information and/or notes are provided for you to read and use to ensure that you can satisfy the assessment requirements for this unit.

Work health and safety (WHS)

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0064), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to WHS and their associated knowledge evidence and performance evidence:

1.1 - Work health and safety (WHS) requirements and workplace procedures for relevant work area are identified, obtained and applied (UEECD0007 references: 1.2, 1.3 & 1.4)

1.2 - Risk control measures are applied in accordance with workplace procedures prior to commencing work (UEECD0007 references: 1.2, 1.3 & 1.4)

2.1 - Workplace risk control measures and procedures are applied (UEECD0007 references: 1.1, 1.6, 2.1 and 2.4)

2.2 - Need to test and measure live work is determined in accordance with WHS requirements and workplace procedures (UEECD0007 references: 1.2, 1.3 & 1.4)

3.1 - WHS work completion risk control measures and workplace procedures are followed (UEECD0007 references: 3.1 to 3.4)

3.2 - Worksite is cleaned and made safe in accordance with workplace procedures (UEECD0007 references: 2.6)

Source: https://training.gov.au/Training/Details/UEEEC0028

As you may already be aware:

- WHS is taught and assessed in a dedicated unit, CD0007 (formerly E101A)
- CD0007 or E101A is a pre-requisite unit for undertaking EC0064 (that is, you must have successfully completed CD0007 or E101A to be able to undertake EC0064)
- The performance criteria listed above are underpinned by, and/or are identical in substance to, the performance criteria in CD0007 and E101A indicated in brackets above
- You have successfully met the assessment requirements for at least one or more of the following units which also include the performance criteria listed above: EC0066/H113A, EC0067/H139A, EC0069/H112A and EC0074/H114A.

Importantly, the knowledge and skills needed to perform these performance criteria are identical to those needed to repair resonance, amplifier and digital circuits operated from mains. This means that you already have the ability to demonstrate your knowledge of, and demonstrate your ability to carry out, these performance criteria in the context of this unit.

However, if your unsure and would like to read more information about these performance criteria, please refer to your learner resources for CD0007/E101A that specifically address them.

Note: If you have not successfully completed CD0007 or E101A, please bring this to the urgent attention of the teacher before undertaking any of the simulated workplace tasks.

Using sustainable energy practices

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0064), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criterion:

2.6 - Problems are solved without unnecessary damage to apparatus circuits, the surrounding environment, or services applying sustainable energy practices.

This includes knowing about sustainable energy principles and practices.

Sustainability is a much used word now that describes growing global response to the short and long term negative effects on the planet of certain human activities, particularly in relation to climate change and pollution. It's accepted that, without drastic action, both problems will likely make living on this planet more difficult (due to extreme weather and toxic environments) that, in turn, risk causing drought, famine, war and the failure of democratic governments and even whole nation states.

R J Fuller (Deakin University, 2005) describes four principles that underpin sustainability:

- Futurity - The concern for future generations
- Environment - The concern to protect the integrity of eco-systems
- Equity - The concern for the poor and disadvantaged
- Participation - The notion that individuals can participate in decisions affecting them

An essential element of the global response to climate change is the switch to sustainable energy. Energy is said to be sustainable if it "meets the needs of the present without compromising the ability of future generations to meet their own needs." Underpinning this are the sustainable energy principles which include (but are not limited to):

- Reducing our use of non-renewable energy sources (like the fossils fuels which includes coal, gas and oil)
- Increasing our use of renewable sustainable energy sources (like solar just to name one of many)

Fuller's fourth principle is important because it means that individuals, including you, can contribute directly and indirectly to sustainable energy principles by using sustainable energy practices where possible. Direct action that can be taken includes (but is not limited to):

- Switching off equipment not in use
- Turning off lights when leaving a room with nobody in it
- Opening windows to cool rooms instead of turning on room air-conditioning
- Using natural lighting
- Minimising waste
- Recycling waste
- Using public transport to and from work
- Drinking tap water

Indirect action that can be taken, includes (but is not limited to) encouraging your employer to:

- Using more energy efficient lighting
- Using more energy efficient equipment
- Reducing (in winter) and increasing (in summer) the temperature setting of air conditioning so that to uses less energy
- Switching to using sustainably sourced and/or sustainably manufactured materials
- Switching to an SEU energy provider

With all that said, every workplace is different so what works with one may not work with another.

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Communication and documentation

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0064), you're expected to demonstrate your knowledge of, and demonstrate your ability to carry out, the following performance criteria related to workplace communication and documentation and their associated knowledge evidence and performance evidence:

1.3 - Nature of oscillator problems is obtained from documentation or relevant person/s to determine scope of work

1.4 - Instructions for coordinating work with others are obtained from relevant person/s and applied

1.5 - Materials required for the work are determined in accordance with workplace procedures

1.6 - Tools, equipment and testing devices required for work are obtained and checked for correct operation and safety.

2.3 - Circuits are checked and isolated, as required, in accordance with WHS requirements and workplace procedures

2.5 - Unplanned situations are dealt with safely and with approval of relevant person/s

3.3 - Justification for solutions used to solve circuit problems is reported in accordance with workplace procedures and job specifications

3.4 - Work completion reporting is completed and relevant person/s notified in accordance with workplace procedures

The specific knowledge required to satisfy these performance criteria is specific to each workplace setting. However, the skills are generic and so are transferable between workplace settings including simulated workplace settings at TAFE NSW. This means that, when you undertake the in-class simulated workplace tasks and the practical test, you are expected to demonstrate your skills in this regard.

Importantly, while undertaking the in-class simulated workplace tasks and/or the practical test for this unit at TAFE NSW, the following applies to key terms in the performance criteria above:

- "Relevant person" refers to the class teacher
- "Others" refers to the class teacher and other students in the class
- "Materials" refers to components and training aids needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list
- "Workplace procedures" refer to the written and verbal procedures and instructions provided by the teacher for the safe and proper conduct of skill practise exercises
- "Tools, equipment and testing devices" refers to tools and test equipment needed to carry out the simulated workplace tasks as described in the skill practise exercises' equipment list and/or mounted on the workbenches

The following is the procedural requirement for undertaking the simulated workplace tasks that form the basis of skill practise exercises.

- Students must have permission from the teacher to start every skill practice exercise.
- Students must work individually on every skill practise exercise, or in pairs with the permission of the teacher (but never more than two per group).
- Students must perform a WHS risk assessment at the start of every skill practice exercise to ensure the safety of themselves and others.
- Students are to bring to the attention of the teacher any hazards that they identify for which there are they cannot implement appropriate control measures.
- Students are to collect equipment from the trolley in a safe and orderly manner having respect for the reasonable needs of other students.
- Students are to follow the written instructions in every skill practice exercises in correct order and in total including any qualifying notes.
- Students are expected to record their measurements, other results and answers to questions for every skill practice exercise and/or any handouts that must be submitted to the teacher.
- Students are expected to call the teacher to check their work when instructions direct them to do so.
- Students are expected to retake any measurements and reattempt and/or correct any of their answers to questions when reasonably directed to do so by the teacher.
- Students are not to return their equipment to the trolley or leave **until** they have completed the skill practice exercise and their work has been checked by the teacher.
- Students are expected to submit their work to the teacher by the due date when required to do so.
- At the completion of every skill practice exercise, students are expected to return all equipment to the trolley tidily (unless directed otherwise by the teacher) and ensure that the workspace is left cleaned and safe.
- Students are to bring to the attention of the teacher any faulty test equipment, tools and components.

Other knowledge and/or performance

When you undertake the in-class simulated workplace tasks and/or the practical test for this unit (EC0064), you're expected to demonstrate your ability to:

- Correctly and accurately take measurements
- Determine live testing /measurement requirements
- Isolate circuits/machines/systems

If your unsure that you are able to demonstrate your ability carry these tasks out, the following notes have been provided here for your convenience for you to read.

Making and analysing measurements

When fault-finding power supplies, the process involves making voltage, current or resistance measurements and comparing them to the values that they should be. These can either be predicted or provided by the manufacturer.

When measuring potential differences, the voltmeter is connected to the circuit in parallel with the component whose potential difference you want to measure. This is shown in Figure 1 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the potential difference across the resistor. The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

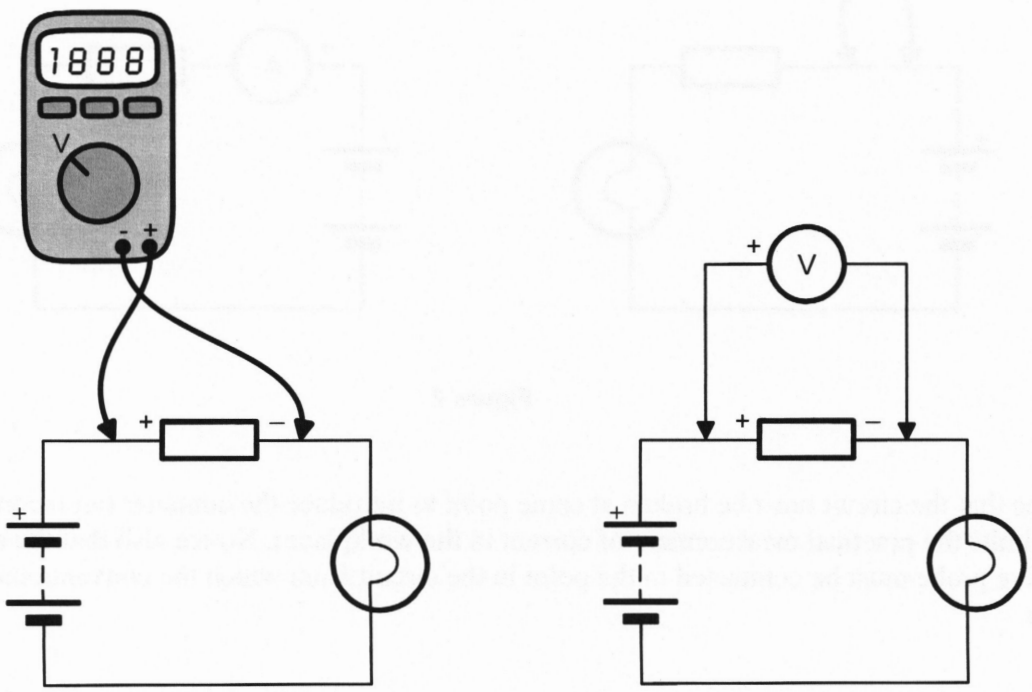

Figure 1

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Notice that the voltmeter's positive probe must be connected to the potential difference's positive side. So, you must determine which side of the component is positive before you connect the meter. The simple rule for this involves recalling that, for all components except the EMF, the side of the potential difference that is positive is the side that conventional current enters the component.

Care must be taken when connecting the meter to the circuit so that you don't actually short two points of the circuit together. This is especially a risk when measuring the voltage on the leads of transistors and the pins of integrated circuits because they're so close together.

When measuring currents, the ammeter is connected to the circuit in series with the component whose current you want to measure. This is shown in Figure 2 below using a simple series circuit consisting of a resistor and a lamp with the meter measuring the current through the resistor (which is also the current through the lamp in this case because it's a series circuit). The meter is shown both as a drawing (on the left) and as a schematic symbol (on the right).

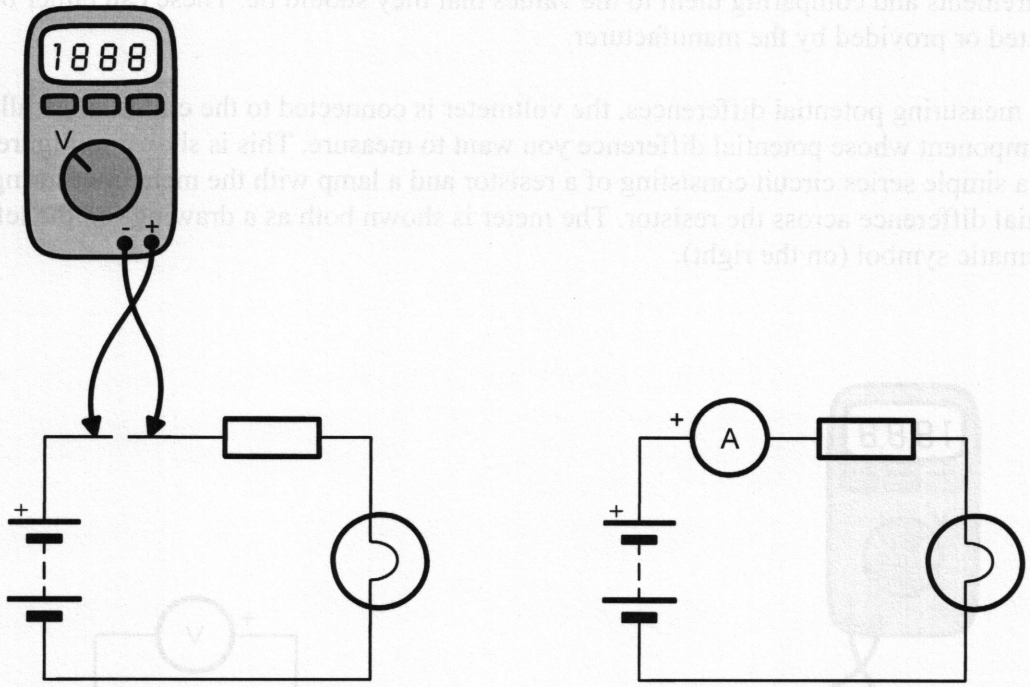

Figure 2

Notice that the circuit must be broken at some point to introduce the ammeter (an inconvenience that limits the practical measurement of current in the workplace). Notice also that the ammeter's positive probe must be connected to the point in the circuit from which the conventional current flows.

Measuring resistance is a simple matter of connecting the meter's probes across the component in any polarity as shown in Figures 3 below. Importantly though, recall that the component should be removed from the circuit before you make the measurement.

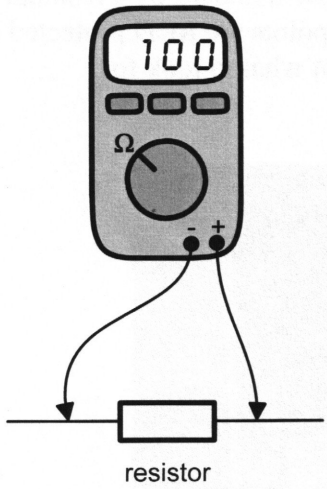

Figure 3a

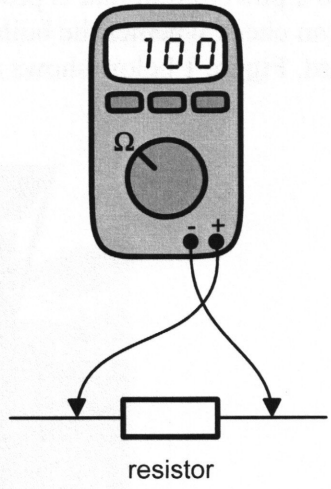

Figure 3b

Also remember that your fingers should not be touching the metal parts of the probes. If the component is out of the circuit, you're not going to get electrocuted. However, if you're touching the metal parts of both probes, the ohmmeter may show an incorrect resistance for the component because the measurement will include your bodily resistance.

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Determining live testing/measurement requirements and isolating circuits

When using a multimeter or oscilloscope to test and measure electronics equipment, there are two important safety measures that can minimise the risk of your being fatally electrocuted.

The first involves ensuring that the equipment that you're testing or repairing (like a hi-fi or PVR) is plugged into a power point that is protected at the switchboard by a residual current device (RCD). You can check whether the building's powerpoints are RCD protected by looking inside the switchboard. Figure 1 below shows an example of what to look for.

Figure 1

Up close, RCDs look like the example in Figure 2 below and there should be at least one row of these devices in the switchboard mounted side-by-side. RCDs are easily recognised by the fact that they're switched devices and often they have an in-built test feature too.

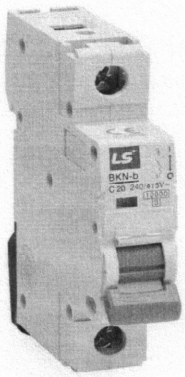

Figure 2

RCDs have been designed expressly for the purpose of preventing people and animals from a sustained direct connection to mains which can be fatal.

If the switchboard is older it may use semi-enclosed cartridge fuses instead of RCDs and an example is shown in Figure 3 below. Importantly, being fuses, these devices are designed to protect equipment and prevent fires but they **do not** prevent people/animals from potentially fatal electrocution. You should avoid powering the equipment that you're testing/reparing from power points that are only protected at the switchboard by these fuses.

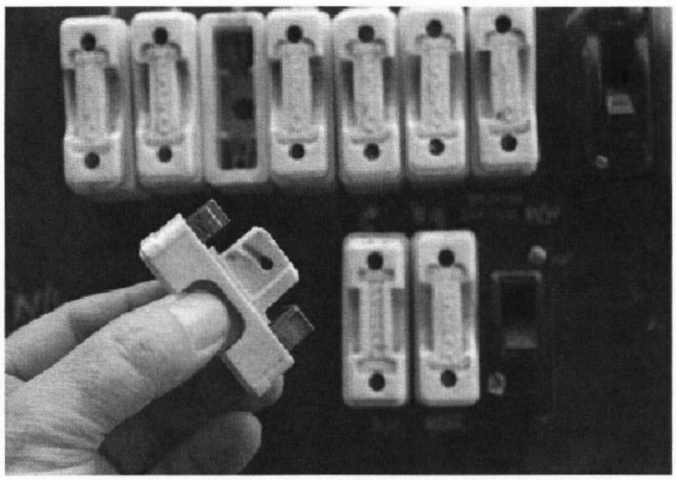

Figure 3

If you can't access the switchboard to see what's inside, or you know for certain that the power point is not RCD protected, then plug the equipment that you're testing into the powerpoint of a powerboard that is RCD protected instead. An example is shown in Figure 4 below - Notice the RCD at the left end (which includes a button for the test feature).

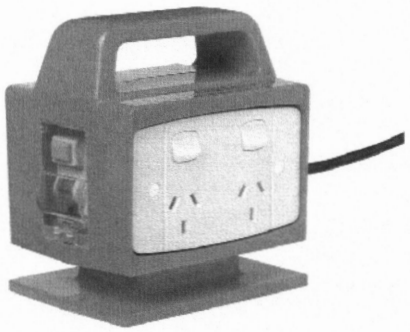

Figure 4

Take care when purchasing protected powerboards because there are many that offer "surge" and/or "overload" protection. While these features are useful, they don't provide protection from electrocution. Powerboards that are RCD protected will state this clearly and are usually a fair bit more expensive than simple surge and overload protected powerboards.

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The second safety measure you must employ when connecting multimeters to live equipment, involves never doing so with your fingers touching any of the probe's metal parts. Figure 5 below shows the correct way to hold the probes. Notice that the person holds the probes behind the their slip barriers.

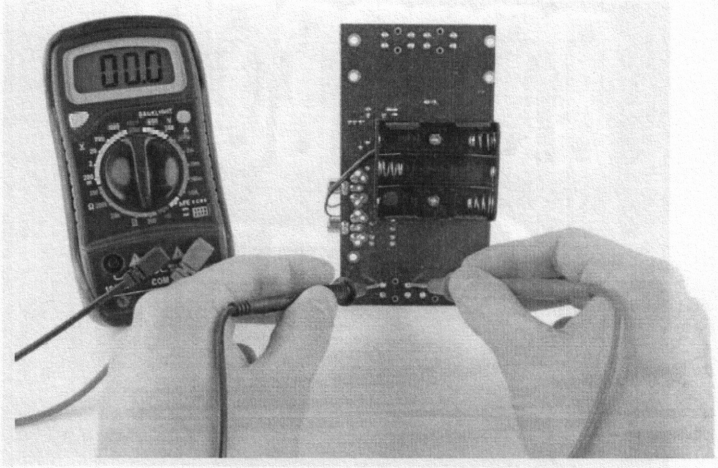

Figure 5

Section 1 An introduction to oscillators

Purpose To develop your understanding of the principle of operation that underpins some sinusoidal oscillator circuits and to give you some general fault-finding strategies that may be used when trouble-shooting these circuits.

Objectives At the end of this section you should be able to:

- Draw the schematic symbol for sinewave, squarewave and triangular wave oscillators
- List electronics equipment that is likely to include an oscillator as one of its functional blocks
- Explain positive feedback with regard to the general feedback model
- Determine the loop gain and loop phase shift
- List and explain Barkhausen's Criteria for oscillation
- Define the term *instability* with regard to oscillators and explain why it occurs
- List four fault-finding considerations that are applicable when first checking any faulty oscillator circuit

Introduction

This chapter introduces you to the theoretical principles that underpin the operation of some sinewave oscillators culminating with Barkhausen's Criteria for oscillation. But first, let's consider what oscillators actually are.

What is an oscillator?

In electronics, *oscillators* are circuits that produce AC signals from a DC power supply. The schematic symbols used to represent a sinewave oscillator in block diagrams is shown in Figure 1 below.

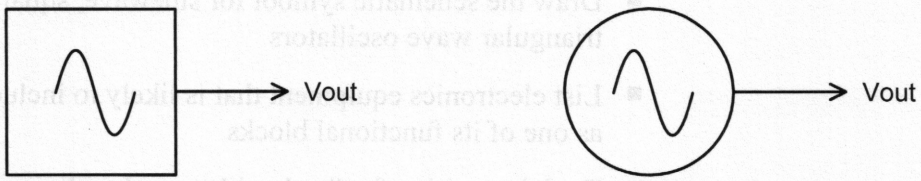

Figure 1 *Block diagram symbols for a sinewave oscillator*

Symbols for squarewave and triangular wave oscillators are also shown in Figure 2 below

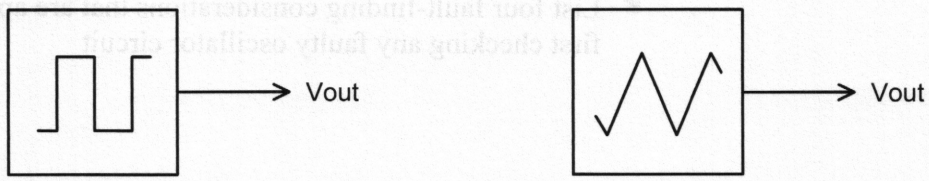

Figure 2 *Block diagram symbol for an oscillator*

For squarewave and rectangular wave oscillators that output a signal with peak voltages that match the two acceptable input voltage ranges for TTL or CMOS logic devices, the oscillator is more likely to be called an *astable multivibrator*.

To the novice, an oscillators can easily be confused with an amplifier because both use a DC power supply to develop an AC waveform on their output. However, there is a big difference between the two circuits. To see that difference, compare their schematic symbols in Figure 3 below.

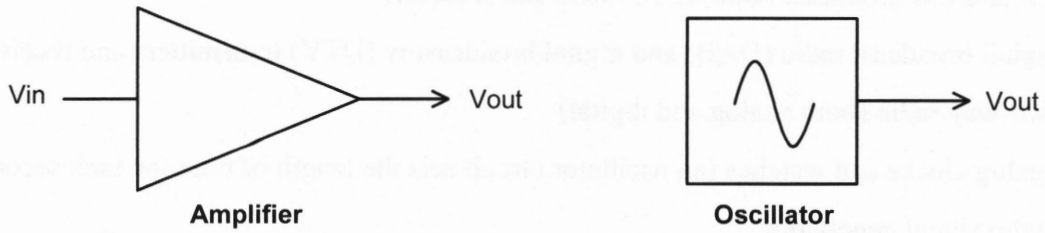

Figure 3 *The schematic symbols of an amplifier and an oscillator*

First, note that neither symbol shows the necessary DC power supply connections because it's understood that they must be present otherwise neither circuit would work. So, with that in mind, we can see that oscillators are different to amplifiers because they don't have a signal input. Recall that the signal on the output of an amplifier is a copy of its input signal (though probably a different size). The output of an oscillator is not a copy of any input signal because there isn't an input. The output signal is created by the oscillator.

That said, an oscillator is **not** an *AC generator*. Oscillators need a DC power supply to operate whereas AC generators don't. Depending on the type, generators burn petrol, gas or coal to cause the rotor to turn which creates a potential difference across a fixed winding that can be used to power electrical/electronics equipment.

Also, an oscillator is **not** an *inverter* like the uninterruptable power supply (UPS) or the unit that's used to connect a PV generation system on a rooftop to the grid. It's true that inverters convert DC to AC. However, the amplitude of the AC output voltage is typically at mains voltages so that the inverter can be used to power electrical/electronics equipment. (With that said, inverters do make use of oscillator circuits.)

Applications

Most electronics equipment have at least one oscillator as part of their circuitry. Below is a list of examples separated into two groups: sinusoidal (ie sinewave) oscillators and digital oscillators.

Sinewave oscillators

- AM and FM broadcast radio transmitters and receivers
- Digital broadcast radio (DAB) and digital broadcast tv (DTV) transmitters and receivers
- Two-way radio (both analog and digital)
- Analog clocks and watches (an oscillator circuit sets the length of time for each second)
- Audio signal generators

(It may surprise you that digital radio and tv use sinewave oscillators. But, while the intelligence transmitted is in digital form, it's superimposed onto a sinusoidal "carrier", just as it is with AM and FM broadcast radio and just as it was once with analog tv.)

Digital oscillators

- Digital radio and tv communications (for the ADC that converts the intelligence into data)
- Digital clocks and watches (for the same reason as analog clocks and watches)
- Computers - the *system clock* signal is produced by an oscillator (an astable multivibrator).
- Gaming machines (eg Playstation) - these are microprocessor-controlled machines much like computers and therefore need a clock signal.
- VCRs, DVD players, CD players, etc - these are usually controlled by microcontrollers and so need a clock signal to function normally and to keep the time.
- Mobile phones - these need oscillators for a number of tasks including the clock for the microprocessor and to generate a carrier signal
- Test equipment - most test equipment need oscillators for their operation but this especially includes function generators, radio frequency (RF) generators that can output digital message signals, and pulse generators.

Closed-loop systems

Many of the things that we experience as isolated events in our natural world are actually a part of a system. Take rain for example. We may think of rain as simply the falling of water from clouds in the sky. However, this "falling of water" is only one part of a system that includes: the formation of streams and rivers; the flowing of rivers into seas and oceans; the evaporation of this water; the formation of clouds and; ultimately, rain again.

There are many such systems in our natural world. Cows eating grass in a paddock produce manure which helps the grass to grow more quickly so that it may be eaten by cows. Clotting blood that seals a small wound actually encourages more blood to flow to the wound. This extra blood clots as well which further helps to seal the wound and encourages still more blood to flow to it and so on. These cyclical processes are all said to be examples of closed-loops systems.

The closed-loop has been used to great advantage in our human-made world to help make it work. An oven would quickly become too hot if the temperature inside wasn't sampled and used to turn off the element that heats it. Even driving a car is an example of a closed-loop that involves you and the car steering system. As you approach a bend, you see the change in road direction and turn the steering wheel so that the car follows the road. If you didn't, the car would carry on in a straight line and run-off the road. And, as already mentioned, the closed-loop is crucial to the operation of most oscillator circuits.

A general definition for a closed-loop system

A closed-loop system is said to be one that returns a portion of its output to its input to affect the system's overall performance. In electronic systems, the "output" is usually a voltage or current. Closed-loops are used extensively in electronics and you only have to think of an operational amplifier (op amp) for an obvious example. Recall that the op amp can be used in one of two modes: the open-loop mode and, much more often, the closed-loop mode.

The general feedback model

An electronic closed-loop system can be represented by the general feedback model shown in Figure 4.

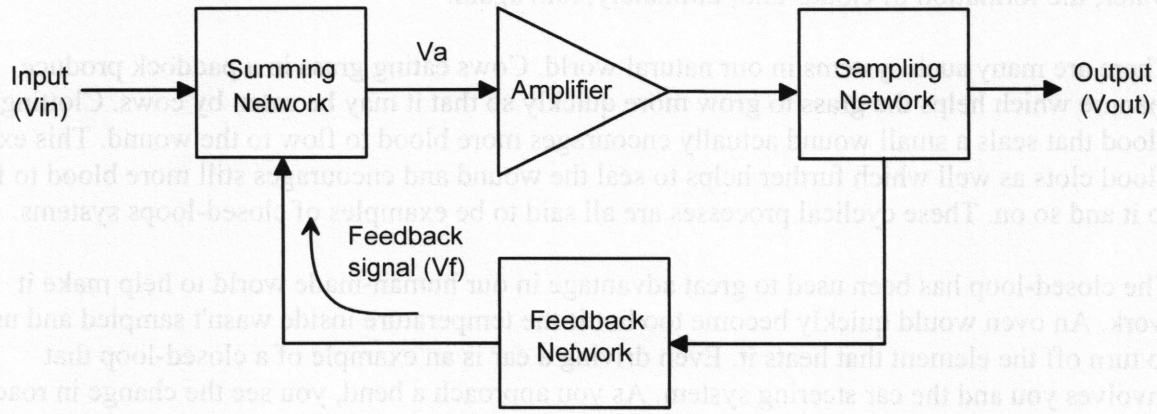

Figure 4 *The general feedback model*

Summing network

As its name implies, this block outputs a signal (*Va*) that is the addition of two inputs: the input signal (*Vin*) and a feedback signal (*Vf*). The summing network may be implemented by something as simple as resistive networks.

Amplifier

In terms of a general feedback model, the amplifier can be either a voltage, current or power amplifier. However, for simplicity, a Class A voltage amplifier is used for this discussion. In practical terms, the function of the summing network and amplifier are usually combined and handled by a differential amplifier.

Sampling network

This functional block refers to the physical connection of the feedback network to the amplifier's output and is not necessarily a circuit. The connection can be in parallel with the load (and therefore sample output voltage) or in series with the load (and therefore sample output current).

Feedback network

The feedback network is a circuit usually made from passive components such as resistors, inductors and capacitors. Its job is to process the sample of the output (to make it smaller but also to provide some phase shift as well) and return it to the input of the system via the summing network to affect the system's performance.

The voltage relationship between the feedback network's input and output voltages is known as the beta (β) and can be calculated using the equation:

$$\beta = \frac{Vf}{Vout}$$

Where: Vf is the output of the network
and: Vout is the input to the network

Loop-gain

Although the amplifier and feedback network in Figure 4 form a loop, they are effectively a cascade because the output of the amplifier feeds the input of the feedback network. And, as the input-output relationship of both circuits can be described as "gain", the total gain of the cascade can be calculated in the same way as for other cascaded circuits. In this case, the total gain is called *loop-gain* and is found using the equation:

$$Loop\text{-}gain = A\beta$$

Where: A is the gain of the amplifier
and: β is the gain of the feedback network

For example, suppose that the amplifier's gain is 7 and the feedback network's beta is 0.25. The loop-gain of the arrangement is:

$$Loop\text{-}gain = A\beta$$

$$Loop\text{-}gain = 7 \times 0.25$$

$$Loop\text{-}gain = 1.75$$

Although you've probably seen loop-gain before when studying another unit, understanding of it is critical to understanding the requirements for oscillation as you will see.

Positive feedback

As mentioned previously, the feedback signal is used to change the system's performance. There are two ways this can be done giving us two types of feedback: *negative feedback* and *positive feedback*.

Recall from your previous studies that negative feedback is said to occur when any change in the output signal subsequently causes the output signal to change some more but in the opposite direction and by a smaller amount which stabilises the output. In short, negative feedback attenuates changes on the system's output.

Positive feedback is said to occur when any change in the output signal subsequently causes the output signal to change some more in the same direction. In short, positive feedback amplifies changes on the system's output.

Referring to the general feedback model (see Figure 5 below), positive feedback occurs when a signal out of the loop (*Vout*) produces a feedback signal (*Vf*) that, when added to the input signal (*Vin*), makes *Va* bigger. This must in turn make *Vout* bigger, making *Vf* bigger and so on. For this reason positive feedback is also known as *regenerative feedback*.

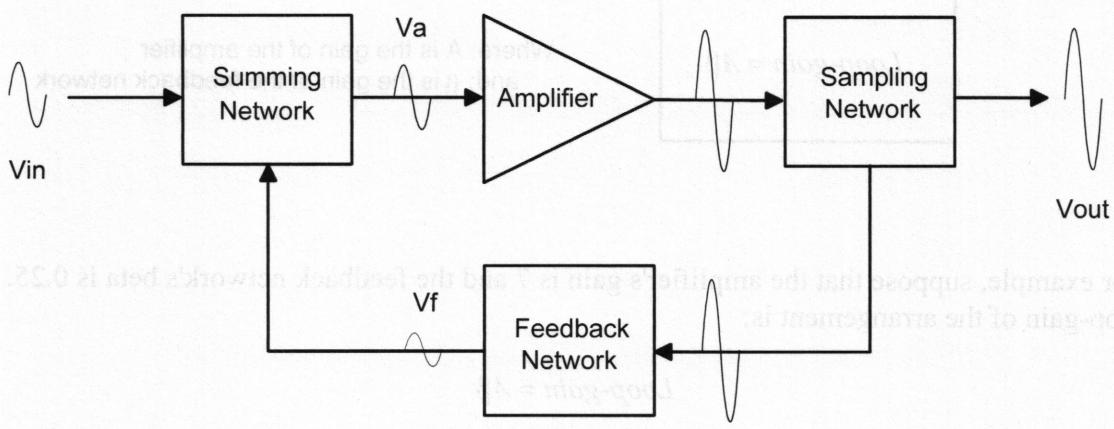

Figure 5 *The instantaneous voltages around a closed-loop system that result in positive feedback*

Positive feedback and sinewave oscillators

Positive feedback is essential to the operation of sinusoidal oscillators for them to start oscillating and, for some circuits, keep oscillating. To explain, consider the closed loop system in Figure 6 below with an input signal connected. (Remember though, oscillators don't need an input signal and one is shown here to build your understanding of the concept.)

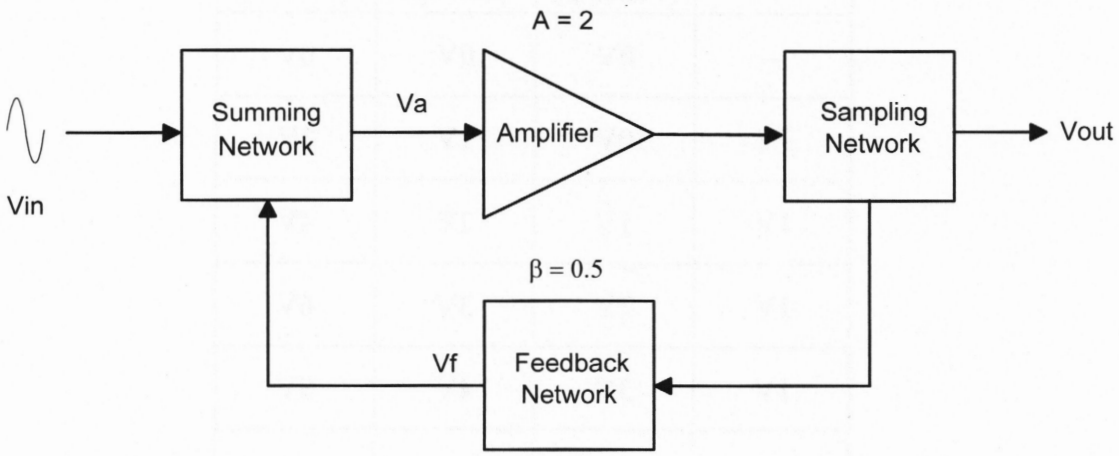

Figure 6 *A closed loop system with a loop-gain of 1*

A quick calculation tells us that the loop-gain is 1 (*loop gain* = 2 × 0.5). Table 1 shows what happens to *Vf*, *Va* and *Vout* for each cycle of the regeneration process when 1Vpp is first connected to the input.

Table 1

Vin	***Vf*** (*Vout* x β)	***Va*** (*Vin+Vf*)	***Vout*** (*Va* x A)
-	0V	0V	0V
1V	0V	1V	2V
1V	1V	2V	4V
1V	2V	3V	6V
1V	3V	4V	8V

Regeneration can be clearly seen in this example. Every time *Vout* gets bigger, it produces a *Vf* that makes *Va* bigger which makes *Vout* bigger still.

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Now, notice what happens when the input signal is removed. Table 2 below shows the same information as Table 1 but with extra rows to show what happens when the input is removed at the moment the output reaches 8V.

Table 2

Vin	***Vf*** (*Vout* x β)	***Va*** (*Vin*+*Vf*)	***Vout*** (*Va* x A)
-	0V	0V	0V
1V	0V	1V	2V
1V	1V	2V	4V
1V	2V	3V	6V
1V	3V	4V	8V
-	4V	4V	8V
-	4V	4V	8V
-	4V	4V	8V

Notice that, once there's an output at the desired level (8V in this example), when the input signal is removed, the system continues to output a sinewave! In other words, we have sustained sinusoidal oscillation. A loop gain of one (often referred to as a *unity* loop gain) is essential for the operation of some oscillator circuits.

What would happen if the loop gain was a value other than one? This is problematic in a few ways but Tables 3 and 4 below show what happens for a loop gain of less than one (Table 3) and a loop gain of more than one (Table 4) at the crucial moment when the input signal is removed.

Table 3 *If A = 2, b = 0.25 then loop-gain = 0.5*

Vin	***Vf*** (*Vout* x β)	***Va*** (*Vin+Vf*)	***Vout*** (*Va* x A)
-	0V	0V	0V
1V	0V	1V	2V
1V	0.5	1.5	3V
1V	0.75	1.75V	3.5V
1V	0.875V	1.875V	3.75V
-	0.9375V	0.9375V	1.875V
-	0.469V	0.469V	0.938V
-	0.235V	0.235V	0.469V

Table 4 *If A = 2, b = 1 then loop-gain = 2*

Vin	***Vf*** (*Vout* x β)	***Va*** (*Vin+Vf*)	***Vout*** (*Va* x A)
-	0V	0V	0V
1V	0V	1V	2V
1V	2V	3V	6V
1V	6V	7V	14V
1V	14V	15V	30V
-	30V	30V	60V
-	60V	60V	120V
-	120V	120V	240V

If the loop-gain is less than 1 then, when the input signal is removed, the regeneration process decays (that is, gradually gets smaller) until the output is zero.

If the loop-gain is greater than 1 then, even when the input signal is removed, the regeneration process continues and runs away to produce ever larger output voltages. In practice, the output signal doesn't keep getting bigger indefinitely; at some point clipping of the output signal would occur as it mathematically exceeded the amplifier's maximum output voltage (which you'll recall is set by the amp's power supply voltage).

[As an aside, you've experienced runaway regenerative oscillation and clipping if you've ever heard the "howl" from a public address system when the microphone is brought too close to the speaker.]

How do oscillators start up?

The previous notes have explained how sustained and undistorted sinusoidal oscillations can be achieved by regenerative feedback (positive feedback) with a loop gain equal to exactly one. But how does the regeneration process start up in the first pace without an input signal?

To answer this question you need to know a little about electrical *noise*. Recall that the atoms that make up any material (including electronic components such as resistors) are vibrating. (They only stop vibrating when the material reaches *absolute zero* or -273°C.) This vibration causes the electrons of some atoms to be shaken-off and they move to other atoms. This movement produces an extremely small noise signal. Importantly, given that the amount and rate of electron vibration is random, the noise consists of all frequencies in the radio frequency spectrum and is called *white noise* (named after white light).

White noise occurs in all electronics systems including oscillators. And, as it theoretically consists of all frequencies in the radio frequency spectrum at some point in time, one of them will be at an oscillator's frequency of oscillation. So, provided the oscillator's closed loop has a loop-gain that is initially greater than 1, the right frequency in the tiny noise signal is regenerated to quickly produce an output. This process is shown in Figure 7 below and Figures 8 and 9 on the next page.

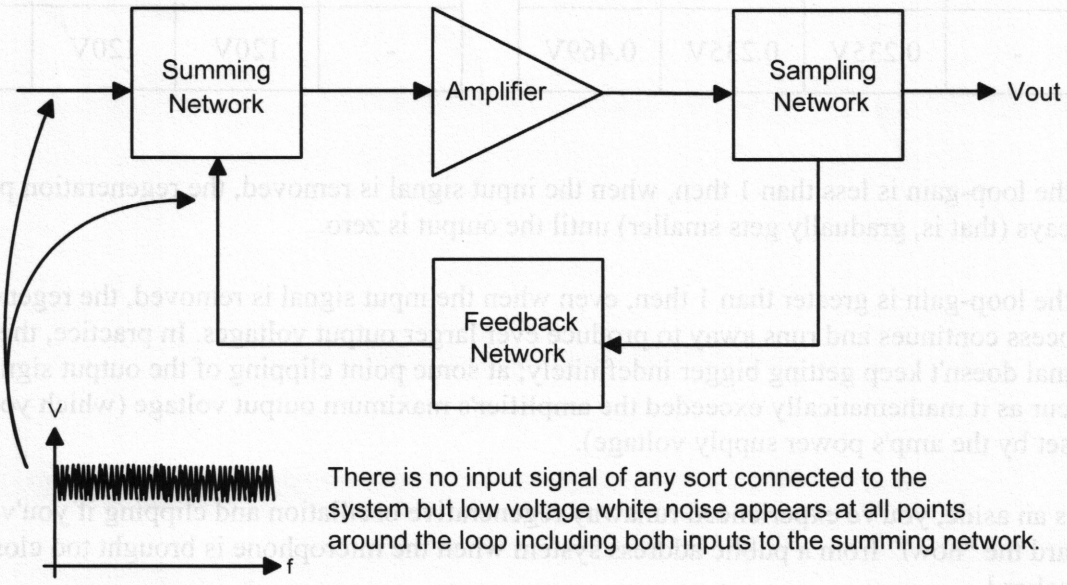
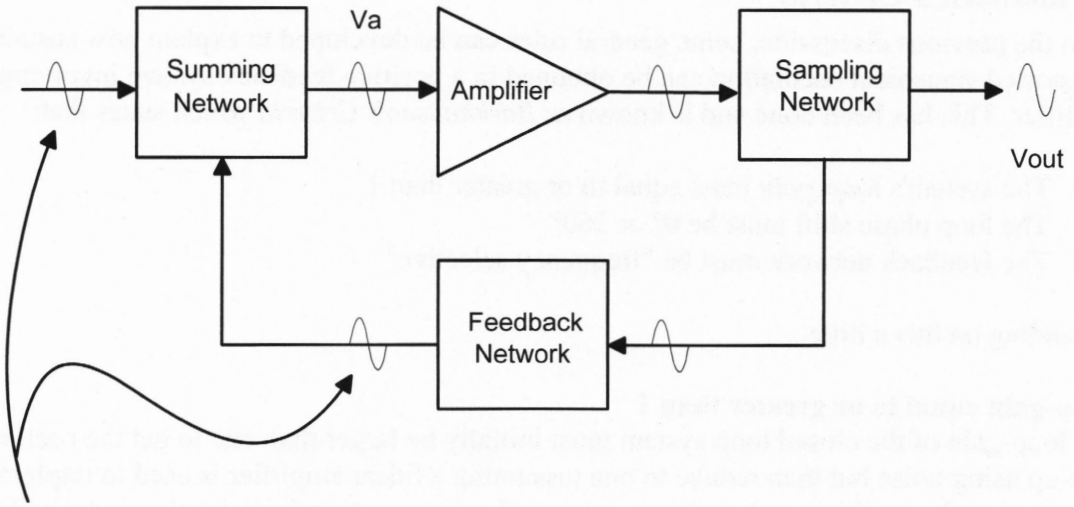
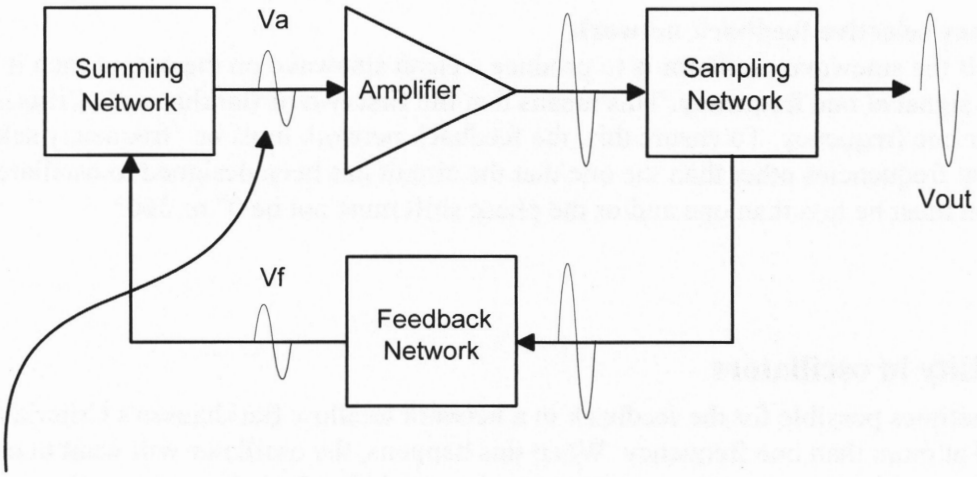


Figure 7



At least one of the sinewaves that makes up the white noise will be in phase at every point around the loop including both inputs to the summing network.

Figure 8



The summing network adds the two noise sinewaves together and, if the loop is greater than 1, the signal will quickly become quite large.

Figure 9

Without some sort of control, the regeneration process would *runaway* and the output signal would be severely clipped (per Table 4). Oscillators that rely on a loop gain of exactly one for sustained undistorted sinusoidal outputs must be designed so that the initial loop-gain is greater than one to get them going but reduces to exactly one once there is an output at the required level.

Barkhausen's Criteria

From the previous discussion, some general rules can be developed to explain how sustained undistorted sinusoidal oscillation can be obtained in a positive feedback system involving a linear amplifier. This has been done and is known as *Barkhausen's Criteria* which states that:

- The system's *loop-gain* must equal to or greater than 1
- The loop phase shift must be 0° or 360°
- The feedback network must be "frequency selective"

Expanding on this a little...

Loop-gain equal to or greater than 1
The loop-gain of the closed loop system must initially be larger than one to get the oscillator to start-up using noise but then reduce to one (assuming a linear amplifier is used to implement the model) once the oscillator gets going to prevent the regeneration from running away and clipping of the output.

The loop phase shift must be 0° or 360°
To achieve positive feedback, the feedback signal and the input signal (which initially is just a part of white noise) must be in phase. This means that the phase shift between the two signals must be 0°. Having said that, a phase shift of 360° means that the shift has come full circle. So a phase shift of 360° is the same as a phase shift of 0° and is also acceptable.

Frequency selective feedback network
Finally, if the sinewave oscillator is to produce a clean sinewave on the output then it can only output a signal at one frequency. This means that the first two of Barkhausen's Criteria must only occur for one frequency. To ensure this, the feedback network must be "frequency selective". That is, at frequencies other than the one that the circuit has been designed to oscillate at, the loop-gain must be less than one and/or the phase shift must not be 0° or 360°.

Instability in oscillators

It is sometimes possible for the feedback in a network to allow Barkhausen's Criteria to be satisfied at more than one frequency. When this happens, the oscillator will want to oscillate at all these frequencies. However, you wouldn't see these as individual sinewaves at the output. This is because the sinewaves add up. Moreover, they interact with each other in several ways (including intermodulating with each other, a process you may learn about in future units) to produce many more sinewaves at different frequencies which also add to the output. The upshot can make the output look very messy and the oscillator is said to have become *unstable*.

Fault-finding oscillators

A former head teacher of the Electronics Section here at Ultimo TAFE once made the following insightful comment about fault-finding electronics: "The two trickiest faults in electronics are oscillators that won't and amplifiers that do."

Amplifiers shouldn't oscillate of course but they sometimes do because most amplifiers are a closed-loop system. Although the closed-loop is set up to introduce negative feedback, poor design or a fault condition can mean that the feedback becomes positive at a frequency and Barkhausen's Criteria are satisfied. This means that the amplifier oscillates as well as amplifies! We'll leave a discussion about what you do in this situation to the relevant subjects.

Returning to oscillators, for any of the blocks in the general feedback model to provide a valid output, two conditions must be met: 1) The block must be functional; and 2) the block's input(s) must be valid. Faulty oscillators can be tricky to repair because, being a closed-loop, every block relies on a valid input from a previous block in the loop. That being case, a faulty block causes the entire loop to breakdown and so it becomes difficult to identify which block is causing the problem.

The notes in this workbook provide tips on fault-finding specific circuits but some generic questions that you need to ask yourself when trying to repair an oscillator circuit include:

- Is the loop physically closed?

  An open-circuit anywhere in the loop due to a dry joint, cracked track or broken component lead breaks the loop and so Barkhausen's Criteria cannot be satisfied.

- Is the oscillator actually faulty?

  Checking the oscillator's output using a standard CRO probe can load the oscillator down and stop it from oscillating. As a general rule, check the oscillator's output using an attenuated (ie 10:1) CRO probe to prevent this problem.

- Is the power supply working and does it connect to every component that it should?

  Both the power supply and common connections to the circuit must be checked.

- Is the oscillator being loaded?

  The oscillator will likely connect to several other system functions. A fault at the input of one of these other functions may be loading the oscillator down, preventing it from doing its job.

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Student notes

Skill practice 1

Developing an advanced understanding of function generator operation

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you'll be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- one BNC-BNC lead

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches). Others: _____ _____ _____	Move bags and other objects from walkways Plan lifting of equipment Other: _____ _____ _____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

Question 1
Locate and record the function generator's output impedance. **Tip:** It's written on the faceplate.

50Ω

Note: This figure is an important attribute of all types of signal generators that you would always be mindful of when using a signal generator or purchasing one for yourself.

3. Use the BNC-to-BNC lead to connect the function generator's **main** output to the CRO's channel 1 input.

4. Set the function generator for a **10kHz squarewave** output at maximum voltage.

5. Measure this voltage and record it in the top row of Table 1 below.

6. Activate the function generator's -40dB attenuation feature.

7. Accurately measure the new output voltage. Record your measurement in Table 1 below.

Note 1: You'll need to adjust the CRO's channel 1 scale control to do this because the signal will be very small now.

Note 2: Let's call the signal's new voltage V_2.

Table 1

Vout without attenuation (V_1)	19.4 V
Vout with attenuation (V_2)	216 mV

8. Prove that this change in the output voltage is -40dB using the equation: $Av_{(dB)} = 20Log\frac{V_2}{V_1}$.

$20Log \times \left(\frac{0.216}{19.4}\right) = 0.011134 \times 20Log(10)$

$= -39.1$ ✓

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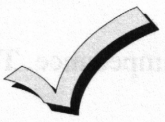


The teacher needs to check your work at this point...

9. Deactivate the function generator's *Attenuation* control and use the CRO to help set it's output to 5Vpp.

10. Set the CRO's input coupling control to the *GND* position and align the trace with the centre horizontal line on the graticule.

    Note: Once done, the graticule's centre line represents 0V.

11. Set the CRO's channel 1 input coupling control to the *DC* position.

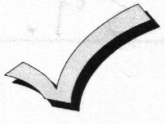
12. Note the voltage of the waveform's positive **and** negative peaks relative 0V.

Question 2
Based on your observation in the previous step, does the waveform consist of any DC voltage? Explain your answer.

No DC voltage in signal!

Question 3
Would this signal be suitable for the clock on a TTL logic IC like a counter? Explain your answer.

No because signal dips below 0V



The teacher needs to check your work at this point...

13. Set the CRO's input coupling control to the *GND* position, align the trace with the horizontal line on the graticule second from the bottom, then set the input coupling back to DC.

14. Connect the CRO's channel 1 input to the function generator's **TTL** output.

15. Measure the voltages for logic-0 and logic-1 relative to the your 0V reference again. Record your measurement in Table 2 below.

Table 2	Logic level	Voltage
TTL output	0	0.6v
	1	5.44v

Question 4
Would non-ideal values for these two voltages be accepted as the correct logic levels to the input of TTL logic gates? Explain your answer in terms of what you learnt about acceptable logic levels on the input of TTL logic devices when you studied digital electronics.

Yes as long as the lower voltage "peak" remains above 0v

Question 5
Why wouldn't this signal be suitable for the clock on a CMOS logic IC with a 9V supply rail (V_{DD})?

CMOS thresholds scale with the supply vdtage

The teacher needs to check your work at this point...

16. Return the CRO's channel 1 input to the function generator's main output.

17. Set the function generator's output signal to a sinewave but leave it at 5Vpp.

18. Turn the function generator's *DC Offset* control to the 12 o'clock position.

19. Activate the DC offset function by pulling the *DC Offset* control's knob toward you.

20. Turn the *DC Offset* control a little clockwise and anti-clockwise and observe the effect that this has on the function generator's output.

Question 6
What does it mean when we say that a signal has a "DC offset"?

whole wave form measurement is shifted up and down across whole screen, average value will not be 0v

Question 7
What's the difference between the DC offset that causes the signal to move up on the CRO's display and the DC offset that causes it to move down the display?

POLARITY

21. Return the function generator's *DC Offset* control to the 12 o'clock position.

22. Increase the function generator's output voltage to maximum.

23. Vary the *DC Offset* control fully clockwise and anti-clockwise and observe the effect that this has on the function generator's output.

Question 8
Why did the output signal clip when you turn the DC offset to maximum in either polarity?

Internal supply rails and output stage limits One side hits the rails when large amplitude is applied

24. Reduce the output signal's amplitude to minimum (**without** activating the *Attenuation* control).

    Note: This mostly leaves just the DC offset component of the waveform on the function generator's output.

25. Turn the *DC Offset* control fully clockwise then measure the maximum positive DC offset. Record your measurement in Table 2 below.

26. Turn the *DC Offset* control fully anti-clockwise then measure and record the maximum negative DC offset.

Table 3

Max positive offset	+ 13.75v
Max negative offset	− 13.8v

The teacher needs to check your work at this point...

27. Use the function generator's *Waveshape*, *Amplitude* and *DC Offset* controls to set up the output for an ideal signal for the input to a CMOS digital IC with a 9V V_{DD}.

Question 9
What is the size of the DC offset needed to produce a signal with this specification?

$V_{HIGH} = V_{OFFSET} + \frac{V_{PP}}{2} = 4.5V$

$V_{DC} = \frac{V_{HIGH} + V_{LOW}}{2} = \frac{9}{2}$

The teacher needs to check your work at this point...

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28. Deactivate the function generator's *DC Offset* and check that its still set to output a 9Vpp squarewave.

29. Read the notes in the breakout box below.

Duty cycle

Duty cycle is a term used to describe an aspect of the shape of pulse trains. To explain it, lets start with a little terminology. When talking about analog signals the upper voltage of a pulse train is called the *mark* the the lower voltage is called the *space*. This is shown in Figure 1 below.

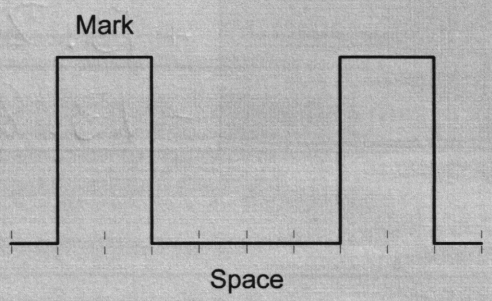

Figure 1

The duty cycle is simply the the duration of the pulse train's mark as a ratio of the period and is usually expressed as a percentage. Using the example in Figure 1 above, we can see that the mark time is 2 units and the period is 5 units. This means that its duty cycle is 40% because 2 is 40% of 5.

30. Activate the *Variable Duty Cycle* control.

31. Vary the *Variable Duty Cycle* control and note the effect on the waveform.

32. Set the signal's duty cycle to maximum.

33. Determine the signal's duty cycle using the equation: $Duty\ cycle = \frac{mark}{period} \times 100$. Record the value in Table 4 below.

Table 4

Minimum duty cycle	16.16%
Maximum duty cycle	50.6%

34. Set the signal's duty cycle to minimum and repeat the previous step.

35. Check to see whether the function generator's TTL output signal can be varied.

Question 10
Can the duty cycle of the function generator's TTL output be varied?

Yes, over a range of 25 to 75%
(Default is 50%)

The teacher needs to check your work at this point...

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If the function generator that you're using is the SFG-1013...

36. Deactivate the function generator's *Duty Cycle* control and return the CRO's input to the generator's main output, if you haven't done that already.

37. Use the CRO to help set the function generator's output to a 12Vpp sinewave.

38. Now press the function generator's *SHIFT* button followed by the decimal point button.

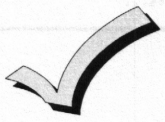
Note 1: The value on the function generator's display will change.

Note 2: Did you notice that the decimal point button has the letters "V / F" written above it in blue? Toggle the display using this control allows it to readout to users the output signal's frequency or its voltage.

Question 11
If you set the output voltage to 12Vpp, why does the display show a value around 6V?

Tip 1: The display isn't showing the output voltage's peak value.

Tip 2: The answer does have something to do with Question 1 and something you've learnt about in several previous units.



The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. What is an oscillator?

2. Draw two schematic symbols for a sinewave oscillator.

3. List 5 pieces of electronics equipment that will have an in-built oscillator.

4. What electronics circuit would not need an oscillator for its operation?

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5. Draw the general feedback model and label each block.

6. Explain the role of each block in the general feedback model.

Summing network:

Amplifier:

Sampling network:

Feedback network:

7. What is another name for the feedback network?

8. What is another name for positive feedback?

9. Why is it called this?

10. What effect does positive feedback have on an electronic system?

11. What type of feedback is necessary to the operation of sinusoidal oscillators?

12. List Barkhausen's criteria for sustained, undistorted sinusoidal oscillation.

13. How is it possible for an oscillator to start oscillating if it doesn't have an input signal?

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14. Calculate the loop gain of a closed-loop system with an amplifier voltage gain of 3 and a feedback network gain (beta) of 0.25

15. Is the loop gain that you calculated for the previous question sufficient for sinusoidal oscillation according to Barkhausen's Criteria? Explain your answer.

16. Calculate the minimum beta needed for Barkhausen's Criteria to be satisfied for the amplifier in Question 14.

17. Why can testing an oscillator with a CRO actually cause an oscillator to stop working?

18. How can this problem be minimised?

19. What are two other considerations when first looking for problems in any faulty oscillator?

Section 2 An introduction to sinusoidal phase shift oscillators circuits using the Wien-bridge Oscillator

Purpose To develop your ability to recognise, understand the operation of, and fault-find sinusoidal phase shift oscillators.

Objectives At the end of this section you should be able to:

- Identify the Wien-bridge oscillator (implemented using an op amp) in schematic diagrams
- Explain how Barkhausen's Criteria is satisfied in the operation of the Wien-bridge oscillator (implemented using an op amp)
- Predict the output waveshape of the Wien-bridge oscillator
- Calculate the frequency of oscillation of the Wien-bridge oscillator given component values
- List some of the limitations/disadvantages of RC phase shift oscillators
- State the advantage of the Wien-bridge oscillator over most other sinusoidal oscillator circuits
- List the likely faults that can occur in the Wien-bridge oscillator (implemented using an op amp)
- Describe the effects of these faults on the performance of the Wien-bridge oscillator (implemented using an op amp)
- Use an oscilloscope to practise making measurements in oscillator circuits and to investigate the operation of a phase shift oscillator (implemented using an op amp)

Introduction

This chapter introduces you to one of the many sinusoidal oscillator circuits that rely entirely on Barkhausen's Criteria for their operation that are generally known as phase shift oscillators. RC phase shift oscillators can be implemented using either transistors or op amps. However, only op amp versions of the Wien-bridge circuit is shown here as it's generally preferred (for reasons not explained as this is an introductory unit on this topic).

The Wien-bridge oscillator

The Wien-bridge oscillator was invented about a hundred years ago. The circuit is the basis of Hewlett and Packard's first commercially released audio signal generator in the 1930s. (For students too young to know, Hewlett Packard was a manufacturer of high quality test equipment before the company spun-off that business in the late 1990s, morphing into the now well known PC manufacturer called HP.)

The Wien-bridge oscillator still finds use today due to the low distortion of its sinusoidal output (distortion figures as low as 0.0003% are apparently achievable) and this is a major advantage of this circuit over most, if not all, other sinusoidal oscillators.

The Wien-bridge oscillator is implemented using an non-inverting op amp circuit which is shown in Figure 1 below.

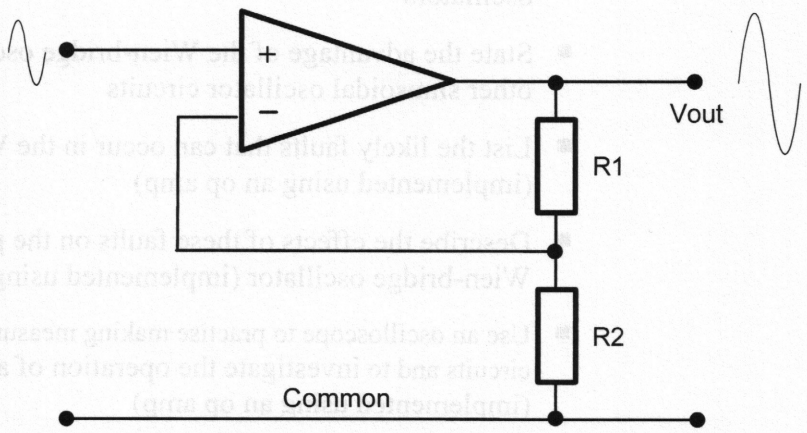

Figure 1 *Non-inverting (op-amp) amplifier*

Recall that this circuit's voltage gain can be calculated using the general equation: $Av = (\frac{R1}{R2}) + 1$.

The equation on the previous page calculates the voltage gain as a ratio and is always a positive number. Importantly, this means that the amplifier introduces 0° of phase shift. This input output phase relationship of the amplifier is also indicated in Figure 1 and explains the circuit's name.

Now, for the non-inverting amplifier to be used as a sinusoidal oscillator, Barkhausen's Criteria dictates that the loop phase shift must be either 0° or 360°. This means that the positive feedback network must also have 0° of phase shift to obtain a total of 0° of phase shift. And Barkhausen's Criteria also dictates that this loop phase shift must only occur for one frequency.

Achieving 0° of phase shift and at only one frequency relies on two simple circuits that you have seen before; the RC low-pass and high-pass filters. These two circuits are shown in Figure 2 below together with graphs of frequency versus gain and phase shift.

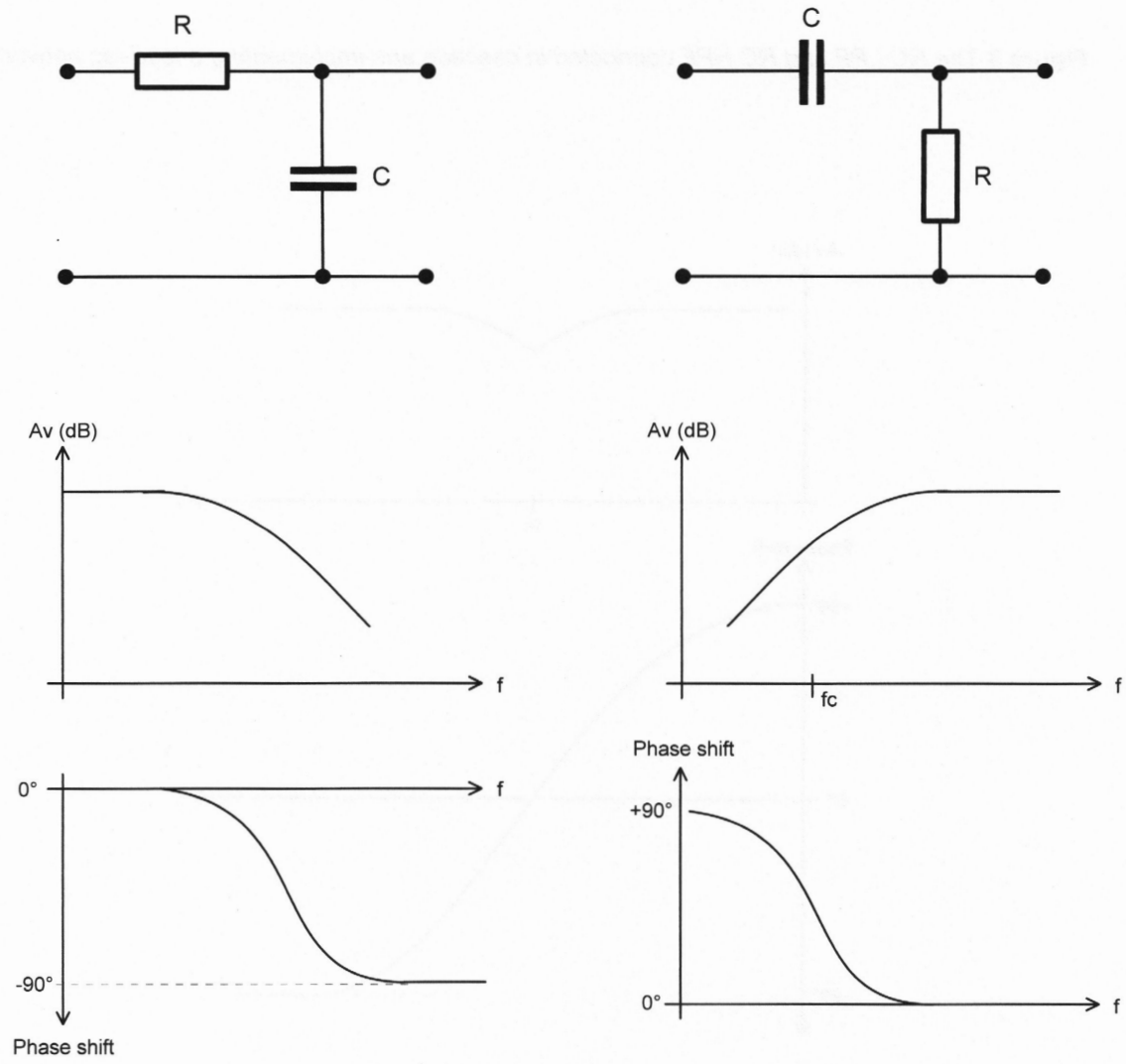

Figure 2 *Left) An RC LPF; and Right) An RC HPF. The graphs below each circuit shows their respective frequency responses*

Importantly, if the resistors in these two circuits are the same value as each other and if the capacitors are the same values as each other then, when they're connected in cascade (as shown in Figure 3 below), we obtain the frequency response and phase shift shown in Figure 4 below.

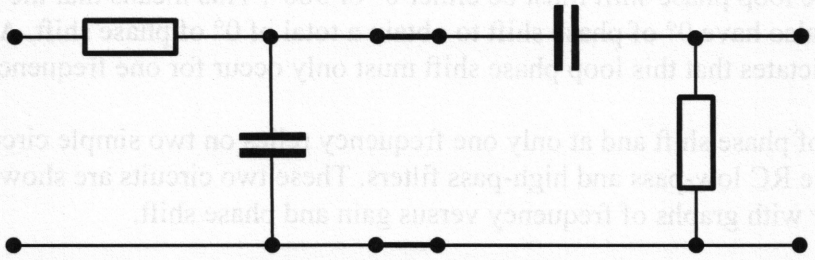

Figure 3 *The RC LPF and RC HPF connected in cascade and implementing a lead-lag network*

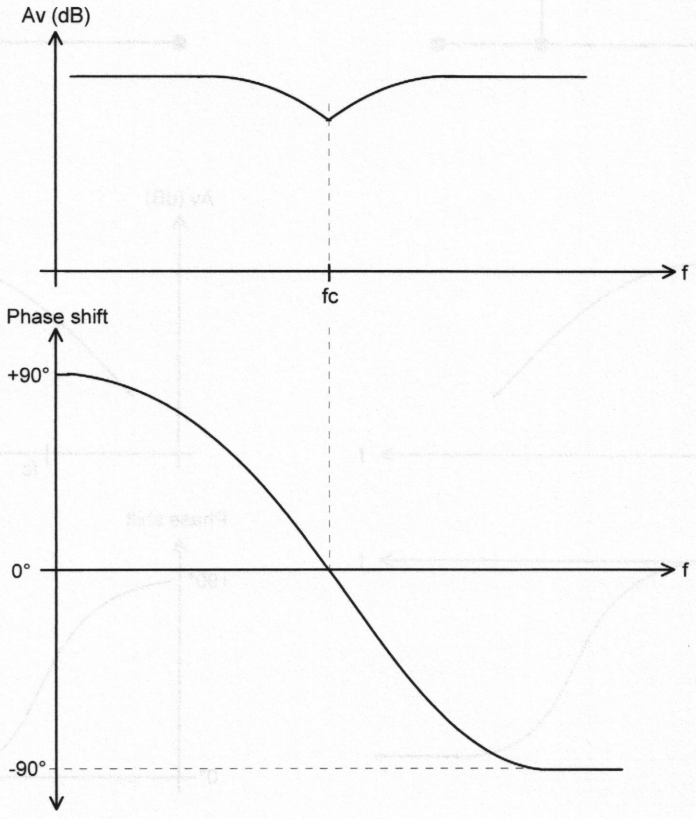

Figure 4 *The frequency responses of the circuit in Figure 3*

The top graph on the previous page shows that the two circuits combined implement a bandstop filter (though not a very good one!).

The much more interesting graph is the bottom one which shows that the circuit introduces a phase shift between the input and output signals from +90° at relatively low frequencies to -90° at relatively high frequencies. It's for this reason that the circuit is called a *lead-lag network*.

To understand why this happens, you need to know that the combined phase shifts of the two circuits is summative. That is, the phase shifts simply add together to give a total phase shift.

Importantly, if you look at the graph closely, you'll see that the circuit introduces 0° of phase shift between its input and output signals (that is, they're in phase) at one frequency and one frequency only. So the circuit is perfect for turning the non-inverting amplifier into an oscillator.

The frequency where the input and output signals are in phase occurs at the cut-off frequency of the two filter sections (assuming their two resistors and two capacitors are the same values). That's because, at the cut-off frequency, the HPF introduces +45° of phase shift and the LPF introduces -45° of phase shift. Adding these together gives 0° of phase shift.

Figure 5 below shows the non-inverting op amp circuit in Figure 1 combined with the lead-lag network in Figure 3 to implement the Wien-bridge Oscillator.

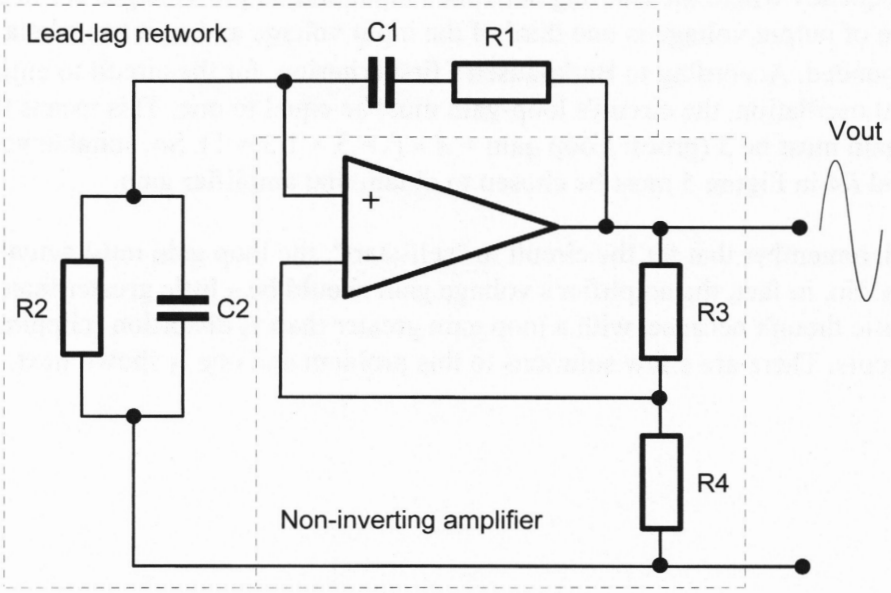

Figure 5 *The Wien-bridge Oscillator*

[As an aside, Max Wien didn't invent this circuit. However, it's based on the concept of a bridge circuit that was first devised by Wien in 1891. Apparently, a man called Frederick Terman was the first to use a bridge to make an oscillator that satisfies Barkhausen's Criteria like this one but he couldn't solve the problem of runaway positive feedback (discussed later). Hewlett was the first to do so and so he has the patent on this design but, given its history, not the eponymist.)

The Wien-bridge oscillator's frequency of oscillation (*fo*) is calculated using the equation:

$$f_o = \frac{1}{2\pi RC}$$

Where: R = R1 = R2
and C = C1 = C2

This is the equation that calculates the two filter sections' cut-off frequency and so it calculates the frequency of oscillation for the reason explained on the previous page.

(Interestingly, the circuit will still oscillate if the either the two resistors and/or the two capacitors in the lead-lag network are not the same value as each other. However, the equation above would no-longer be valid.)

Satisfying Barkhausen's 1st criterion

How the circuit satisfy Barkhausen's 2nd and 3rd criteria has been explained. Importantly, Barkhausen's first criterion must also be satisfied for sinusoidal oscillation.

At the frequency where the lead-lag network's input and output voltages are in phase, the amplitude of output voltage is one third of the input voltage and so it has a beta (β) of 1/3 or 0.3333 rounded. According to Barkhausen's first criterion, for the circuit to enjoy sustained sinusoidal oscillation, the circuit's loop-gain must be equal to one. This means that the amplifier's voltage gain must be 3 (proof: Loop gain = $A \times \beta = 3 \times 1/3 = 1$). So, suitable values of resistance for *R3* and *R4* in Figure 5 must be chosen to obtain that amplifier gain.

That said, remember that for the circuit to "self-start", the loop gain must actually be greater than 1 initially. So, in fact, the amplifier's voltage gain should be a little greater than 3. This is problematic though because, with a loop gain greater than 1, distortion (clipping) of the output signal occurs. There are a few solutions to this problem and one is shown next.

Control of the positive feedback

The circuit's loop gain must be greater than 1 for the oscillator to "self-start". However, if the loop grain remains greater than 1, the positive feedback will run away causing clipping on of sinewave on the output. But if the loop gain is exactly 1, the circuit won't self-start.

To solve this conundrum, the early Wien-bridge oscillator designs made use of a thermal resistor (thermistor) in the amplifier's negative feedback path. A negative temperature coefficient (NTC) thermistor can be used in place of *R3* or a positive temperature coefficient (PTC) thermistor can be used in place of *R4*. To explain how a thermistor ensures that there's enough gain for regeneration but not so much that it runs away, an NTC thermistor for *R3* will be used in a circuit (Figure 6).

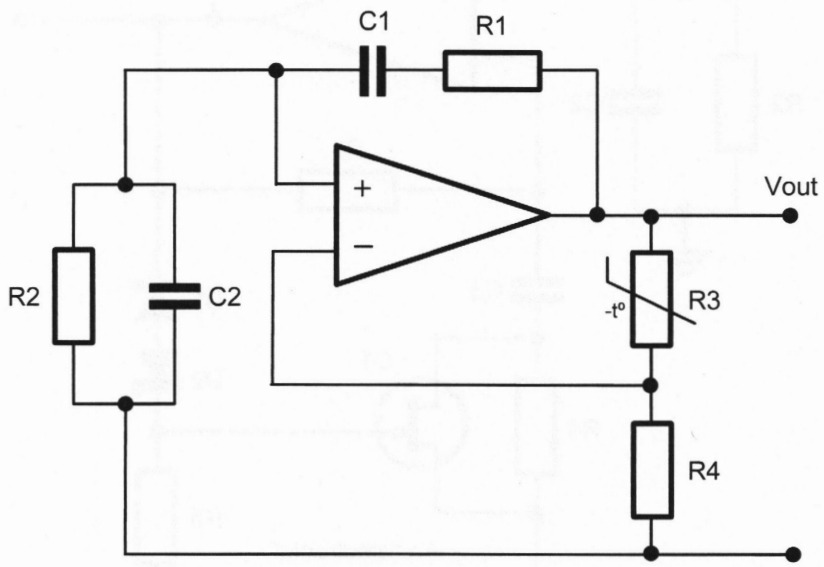

Figure 6 *Wien-bridge oscillator with an NTC thermistor in place of R4 to stabilise the gain*

The value of the thermistor is chosen so that its room-temperature resistance makes the non-inverting amplifier's gain bigger than three and so the circuit's loop-gain is greater than one. This ensures that there is enough gain to start-up the oscillator. Once the oscillator gets going, current flows through *R3* and *R4* warming both components up. As *R3* is an NTC thermistor, its resistance drops, lowering the amplifier's closed-loop gain which in turn lowers the system's loop-gain preventing the regeneration from running away.

The NTC thermistor's value cannot drop so much that the amplifier's closed-loop gain drops below 3 causing the loop gain to drop below 1 and stopping oscillation. That's because of the way the negative feedback works and because of the thermal inertia of the thermistor. Recall that, with negative feedback, every change in the output causes a subsequent change in the output that is smaller than the preceding one. But every change in the output is only partially realised due the time it takes the thermistor's temperature to change and so every change due to negative feedback is smaller than it should have been due to thermal inertia when it causes the next change. The net effect is that the change can never be big enough to cause Barkhausen's first criteria to stop being satisfied.

Despite the cleverness of using a thermistor for gain stabilisation can still be a little clunky (as you'll see in the practical exercise). There are several other methods of achieving this effect and a sophisticated one is shown in Figure 7. In this circuit *R4* is substituted for a circuit that simulates a PTC thermistor. This circuit was taken from the application notes for an electronic device (an op amp, if your author remembers correctly) and you're not expected to recognise it or explain its operation.

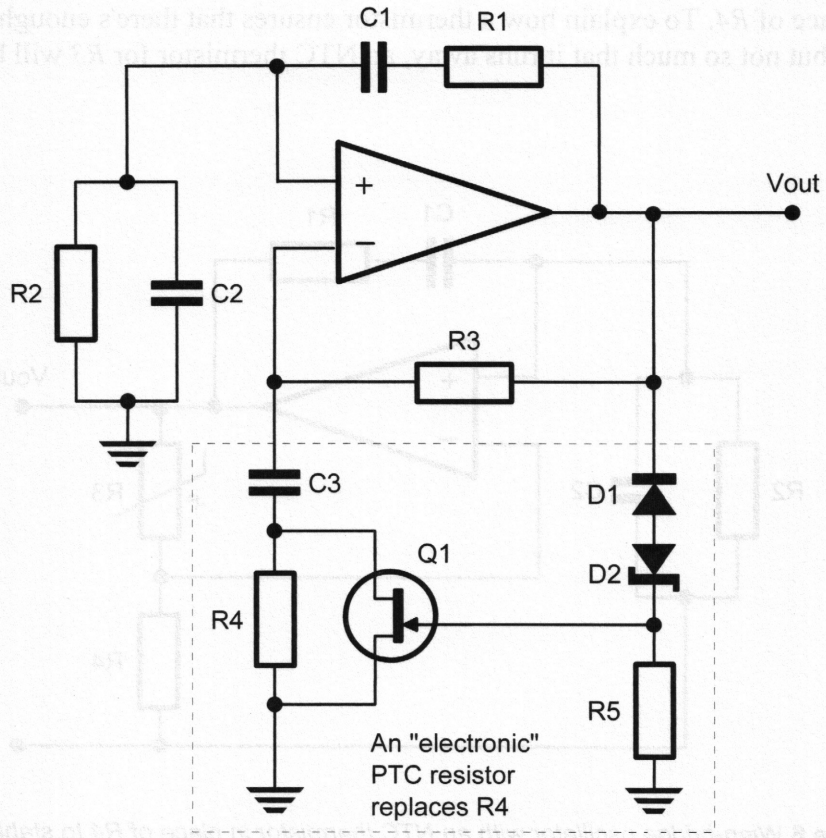

Figure 7 *A Wien-bridge oscillator with an "electronic" PTC thermistor in place of R4*

Limitations

Although the Wien-bridge oscillator is a superior circuit to other oscillators in terms of the low distortion figures that are possible, it suffers from a practical limitation when implemented using an op amp.

The output frequency is limited to relatively low frequencies due to the op amp's bandwidth limitations. To explain, recall that the bandwidth and gain of an op amp is inversely proportional. It's set by the op amp's GBWP figure and the greater the gain, the lower the bandwidth. Taking a respectable op amp GBWP figure of 4MHz, the maximum possible frequency of oscillation for the circuit would be 1.333MHz (proof: BW = $\frac{GBWP}{Av} = \frac{4MHz}{3}$ = 1.333MHz). Attempting to make the op amp oscillate at higher frequencies would involve trying to make it do so in its roll-off region where the open-loop gain, and hence its closed-loop gain, is falling.

Using a BJT in place of an op amp would permit higher frequencies of oscillation but that would bring with it new problems not discussed here. Even if it didn't, the frequency of operation is limited by the difficulty of making small value capacitors with reliable values. Discrete capacitors with a meaningful tolerance are impossible to manufacture below a certain value due to parasitic capacitance caused by the component leads, circuit board tracks, etc.

Inductor-capacitor (LC) oscillators or crystal-controlled oscillators are needed for oscillators at radio frequencies beyond about 1MHz to 2MHz.

Fault-finding the Wien-bridge oscillator

Before discussing specific fault-finding techniques for the Wien-bridge oscillator, let's briefly revisit the questions you should ask yourself when you start the process of fault-finding any oscillator circuit:

- Is the loop still closed?

  Recall that poor solder joints or physical damage to components or the circuit board can break the loop. So, a physical inspection before starting is a good idea. This must necessarily include an connections to the circuit common of the components in the positive feedback network.

- Is the oscillator actually faulty?

  Recall that the CRO you're using to test the oscillator could be loading its output and stopping it from oscillating and deceiving you into thinking the circuit isn't working. To minimise the risk of this problem occurring, use an attenuated CRO probe.

- Is the power supply working and does it connect to every component that it should?

  Recall that amplifiers don't work if they don't have power so check the op amp's power supply connections.

- Is the oscillator being loaded?

  Recall that the oscillator's load may be faulty preventing it from oscillating. Keep this in mind if you can't find a problem with the oscillator.

The following notes assume these issues are attended to at the appropriate point in the fault-finding process and so are not canvassed again.

Problems with the oscillator oscillating at the wrong frequency

Unless an oscillator is crystal-controlled (more in a later chapter), you would expect there to be a difference between the oscillator's theoretical and measured output frequencies.

For a well designed Wien-bridge oscillator, the difference between the theoretical and measured output frequencies shouldn't exceed the tolerance of the components that set the frequency of oscillation (that is, the resistors and capacitors in the lead-lag network).

If the output frequency error of one of these phase shift oscillator's is larger than it reasonably should be then it may be the case that one or more of the resistors or capacitors in the positive feedback network have drifted in value. Age or an environment of elevated temperatures would be possible causes. It's impossible to identify which one of these components is the culprit from circuit voltage measurements. So, the resistors and capacitors would need to be removed from the circuit one at a time and tested using an LCR meter.

(With all that said, if the accuracy of the oscillator's output was crucial to the operation of its load, a crystal-controlled oscillator would likely be used anyway and not this circuit!)

Problems with a clipped output signal

If distortion is not an important performance attribute of these oscillators in terms of the application in which they're being used, then they may be designed to permit a small amount of distortion rather than unnecessarily including methods of controlling the amplifier's voltage gain. In which case, some flattening of the peaks can be expected.

However, in applications where these circuits are expected to produce an undistorted sinusoidal output, but clipping is present, then there's a fault to be found. The problem must be that the method of controlling amplifier's voltage gain is no-longer functioning correctly.

In this unit, we have introduced you to only one method of controlling the amplifier's voltage gain; that is, the use of a thermistor in the op amp's negative feedback path. Assuming the equipment has a history of working correctly then one or both of the resistors in the op amp's negative feedback have drifted in value. Removing and testing the fixed resistor is the logical first step given thermistors change their value anyway with changes in temperature. If the fixed resistor's value is within tolerance, the thermistor likely needs replacing.

Problems with the oscillator not oscillating

If the circuit is not oscillating at all, the problem is unlikely to be one of the resistors or capacitors in the positive feedback network. That's because one of these components will have had to change value substantially, or have completely failed altogether, for the circuit to stop oscillating. But, given the small currents that would flow through them when the circuit is operating, failure due to fatigue is unlikely. Exceptions to this generalisation include; if the equipment is fairly old (in which case one of these components may have simply failed due to age), or if the equipment has been dropped and one of the component leads has sheared through (but this would possibly have been identified earlier when performing a visual inspection of the circuit).

Given the simplicity of the circuit design here, the simplest fault-finding solution would be to remove the negative feedback resistors one at a time to check that they're the correct value. If one or both of them are not the correct value, you have identified the fault. If they are the correct value, then the only component left is the op amp and so it needs replacing.

The fault-finding approach can be a little more sophisticated than this and would be more efficient for circuits implemented using SMD components (because of the difficulty is de-soldering and re-soldering them) or for more sophisticated designs version of these circuits. Moreover, you have been taught how to fault-find op amp circuits in an earlier unit.

For the non-inverting op amp circuit used to implement the Wien-bridge oscillator in Figures 5 or 6, given the circuit isn't oscillating, there would only be DC voltages present in the amplifier circuit. And, as the positive feedback network is connected from the amplifier's output to its input via a capacitor (*C1*), the network can be ignored because capacitors block DC. That said, *R2* would still provide a DC electrical connection to common for the op amp's non-inverting input. All this means that the circuit that you're fault-finding then is reduced to the one shown in Figure 8 on the next page.

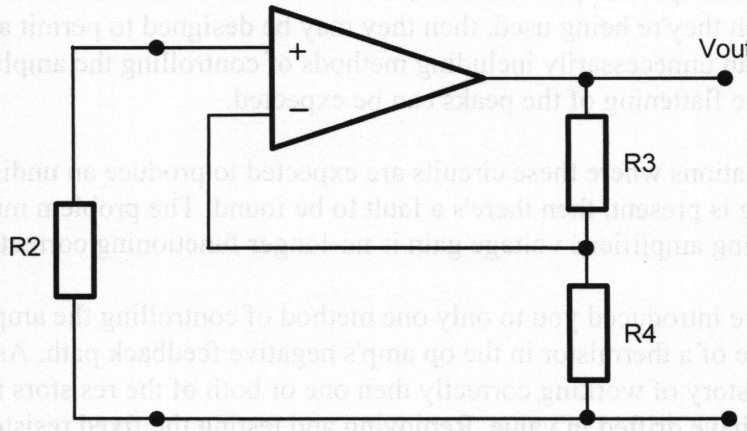

Figure 8 *How the Wien-bridge oscillator effectively looks from a DC perspective when it stop oscillating*

Assuming you have already checked the op amp's power supply voltages, the first voltage to measure is the one on the op amp's output non-inverting input ($V_{\oplus}$) with respect to common.

- If $V_{\oplus}$ is anything other than 0V then you immediately know the op amp is faulty and needs replacing. If $V_{\oplus}$ is 0V the op amp could still be the problem but it could also be either *R3* or *R4*.

The next voltage to measure is the output voltage (*Vout*) with respect to common. It'll likely be either 0V (or close to it) or sitting at a voltage approaching either *+Vcc* or *-Vcc*.

- If *Vout* is 0V, it suggests that either:
  - *R4* is either high or open-circuit.

    Rationale: With *R4* high or open-circuit, the op amp's voltage gain drops below 3 and so the loop gain drops below 1 and the circuit won't oscillate. In which case, with 0V on the op amp's input (via *R2* which is now acting as a simple pull-down resistor), there'll be 0V on its output.

  - The op amp is faulty.

    Rationale: A fault internal to the op amp that open-circuits a key component in both paths from the output to the two supply rails would effectively disconnect its output pin from the circuit inside. This would cause 0V on its output (but not floating due to the path to common via *R3* and *R4*).

If *Vout* is sitting at a voltage approaching either *+Vcc* or *-Vcc* then measure the voltage on the op amp's inverting input (*V-*).

- If *V-* is 0V, it suggests that:
  - *R3* is open-circuit.

    Rationale: *R3 and R4* form a voltage divider. So, if *-V* is 0V then that must mean there is also 0V across *R4*. In turn, that must mean that all of the op amp's output voltage is dropped across *R3* and so it's resistance must be extremely large.

- If *V-* is about a third of *Vout*, it suggests that:
  - The op amp is faulty.

    Rationale: A fault internal to the op amp can create a short-circuit or low path resistance to one of its supply rails. Now, the op amp has a gain of three which is set by the ratio of the two resistors *R3* and *R4*. Importantly, *R3 and R4* form a voltage divider so, as the voltage at *V-* is about a third of *Vout*, these resistors must be ok and that only leaves the op amp as the faulty component.

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Student notes

Skill practice 2

Practise measuring key voltages in a phase shift oscillator (the Wien-bridge oscillator) using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you'll be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Emona Trainer
- Decade box
- DMM
- 741 op amp
- 2k NTC thermal resistor
- two 47kΩ ¼W resistors
- two 5.6nF capacitors
- three BNC to alligator-clip leads
- banana leads
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
■ Trip hazards (eg students bags) ■ Objects dropped on feet (while equipment is taken to and from workbenches). Others: _____ _____ _____	■ Move bags and other objects from walkways ■ Plan lifting of equipment Other: _____ _____ _____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1.

   Note: Ensure that the black alligator-clip of function generator's lead is connected to the circuit's common.

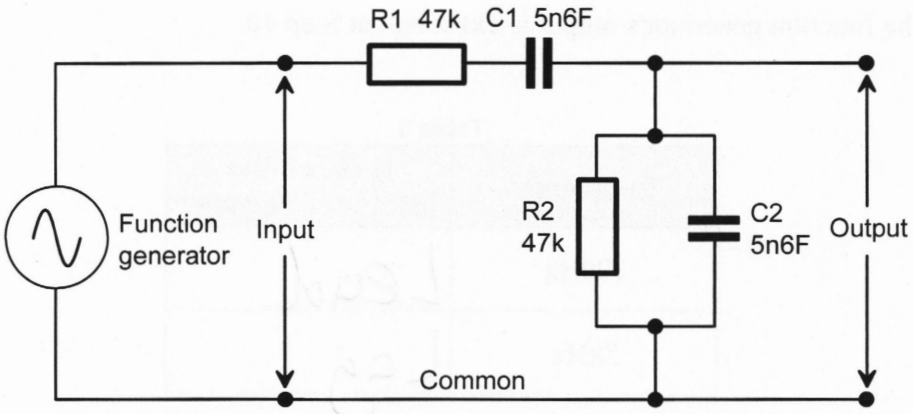

Figure 1

4. Connect the CRO's channel 1 input to the circuit's input.

   Note: All black alligator-clips must be connected together and to the circuit's common.

5. Connect the CRO's channel 2 input to the circuit's output.

6. Adjust function generator to output a 100Hz 3Vp-p sinewave.

7. Adjust the CRO to view both waveforms on the display.

8. Momentarily connect each channel's input coupling control one at a time to ground and centre the channel's trace.

9. Compare the waveforms.

   Note: There should be a phase difference between the two signals. If there isn't, check your wiring.

10. Determine by visual inspection whether the output signal is leading or lagging the input. Record this in Table 1.

11. Slowly increase the function generator's output frequency to 2kHz while watching the two waveforms.

    Note: As you do, you should notice the phase shift between the two signals changes.

12. Once the function generator's output is 2kHz repeat Step 10.

Table 1

Frequency	Is the output leading or lagging?
100Hz	Lead
2kHz	Lag

13. Adjust the function generator's output frequency to find the frequency where the input and output signals are in phase. Record this frequency in Table 2 below.

    Tip 1: It'll be between the two frequencies in Table 1.

    Tip 2: Ensuring that both CRO channels are centred on the display will help you do this. Once the two signals are in phase, they'll both cross the centre line at the same points in time.

14. Measure and record the lead-lag network's output voltage at this frequency.

Table 2

Measured in phase frequency	Output voltage
620 Hz	936 mV

Question 1
Calculate the theoretical frequency where the input and output signals should be in-phase with each other using the equation: $f = \frac{1}{2\pi RC}$.

$\frac{1}{2\pi \times 47k \times 5.6 \times 10^{-9}} = 604.7Hz$

Question 2
Compare the measured frequency in Table 2 with the frequency that you calculated for Question 1. Explain why they're not exactly the same.

Remarkably similar - only 15.3 Hz diff

Within 2.5% tolerance!

Question 3
Calculate the circuit's ratio of output voltage to input voltage at the frequency where the input and output voltages are in phase.

$\frac{0.936}{2.9} = 0.3228 = \sim \frac{1}{3}$

Question 4
What attribute of the positive feedback network does your answer to Question 3 give you?

The feedback factor (β) i.e. the attenuation of the pos. feedback network

The amp must provide gain of 3 so $A\beta = 1$

The teacher needs to check your work at this point...

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15. Measure the resistance of the thermal resistor but avoid touching the body of it as you're doing so. Record the value of resistance in Table 3 below.

Table 3

Resistance	2.4 kΩ

16. Wire the circuit of Figure 2 below.

Note: Don't dismantle the previous circuit because you can use it for the circuit below.

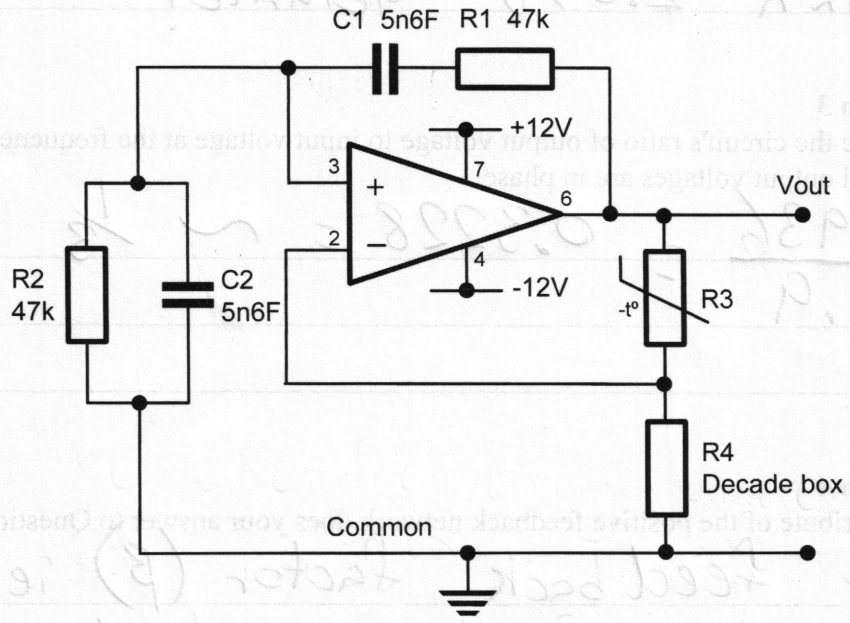


Figure 2

17. Adjust the decade box for 450Ω.

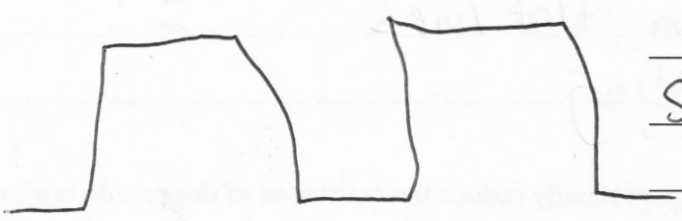
18. Connect the CRO's channel 1 input to the circuit's output.

19. Turn on the Emona Trainer.

    Note 1: Your circuit should start oscillating.

    Note 2: If your circuit doesn't start oscillating, reduce the resistance of the decade box in 10Ω steps until it does. If this doesn't work, turn the circuit off check your wiring very carefully then repeat steps 16 to 19.

20. Once the circuit starts oscillating, draw and describe the waveform that you observe on the output.



Looks like a dipped sine wave

21. Calculate the approximate theoretical closed-loop voltage gain of the op amp using the equation $Av = \frac{R3}{R4} + 1$. Use the measured value of the thermal resistor for *R3* and the value of resistance that the decade box is set for *R4*. Record your value in Table 4.

Table 4

Closed-loop gain (Step 21)	6.33 v/v	**Closed-loop gain** (Step 23)	3.4 v/v

22. Gradually increase the resistance of the decade box until the oscillator's output is an undistorted sinewave. 1190 Ω

    Note 1: You may have to give the circuit a little time to settle after each adjustment while the thermistor's value changes (due the change in the current through it).

    Note 2: You can probably start with 100Ω changes at first reducing them to 10Ω changes as the distortion decreases.

23. Calculate the new approximate closed-loop gain of the amplifier using the new value of resistance on the decade box and record this in Table 4.

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24. Measure the circuit's output frequency. Record your measurement in Table 5 below.

    Note: For accuracy, use the function generator's in-built frequency counter to do this.

Table 5

Frequency	600 Hz

25. Continue to gradually increase the resistance of the decade box and describe what eventually happens at the output.

Smooths then flat lines
Stops oscillating

26. Once the oscillator stops oscillating, gradually reduce the resistance of the decade box and describe what you get once it restarts.

oscillations again

Question 5
What is the significance of the oscillator's frequency of oscillation? **Tip:** If you're not sure, look back at the information in Table 2.

It's the one frequency where the lead lag network gives 0° phase shift (in-phase)

Question 6
Why was the circuit's output distorted when you first got it oscillating at Step 20?
Tip: Answer this question in terms of Barkhausen's Criteria.

output distorted because the oscillator initially had loop gain $A\beta > 1$, the amplitude grew until the op-amp saturated, undistorted operation only occurs when $A\beta$ reduces to ~ 1

Question 7
Calculate the approximate value of the circuit's loop-gain when its output was distorted using the op amp's gain figure that you obtained at Step 21. **Tip:** You calculated the lead-lag network's beta (β) for Question 3.

$A\beta = 1.188 \times 0.3228 = 0.383$ = Loop gain

Question 8
Why did the distortion of circuit's output signal disappear once you increased the resistance of the decade box by enough at Step 22? **Tip:** Answer this question in terms of Barkhausen's Criteria.

Increasing R3 changes the op amps closed loop resistance, so the loop gain reduced to approximately unity ($A\beta = 1$)

Question 9
Calculate the approximate value of the circuit's loop-gain when the oscillator's output is no-longer distorted using the op amp's gain figure that you obtained at Step 23.

Question 10
Why did the circuit's output drop to zero when you continued to increase the resistance of the decade box at Step 25? **Tip:** Answer this question in terms of Barkhausen's Criteria.

Question 11
Why did the circuit start oscillating again when you reduced the resistance of the decade box at Step 26? **Tip:** Answer this question in terms of Barkhausen's Criteria.

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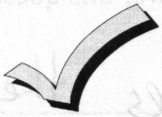
Question 12

Why are your answers to Questions 7 and 9 only close approximate values? **Tip:** The answer is **not** component tolerance.

thermistor in and out of circuit



The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 14 refer to the circuit of Figure 1 below

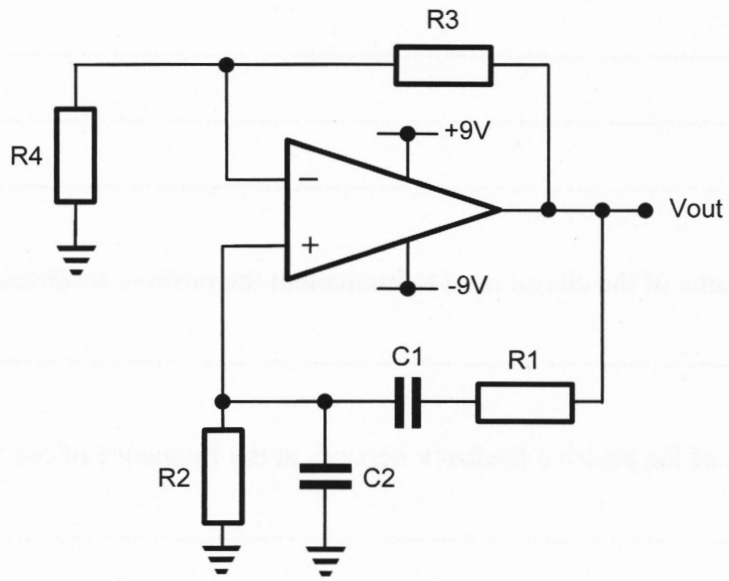


Figure 1

1. What type of oscillator is this circuit?

2. Why is this oscillator particularly suited for testing audio equipment?

3. Calculate the frequency of oscillation if *R1* and *R2* are 10kΩ and *C1* and *C2* are 1nF.

4. What is the input-output phase relationship of the closed-loop op amp amplifier circuit?

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5. What is the input-output phase relationship of the circuit's positive feedback network at the circuit's frequency of oscillation?

6. Explain how your answers to Questions 4 and 5 allow the circuit to satisfy Barkhausen's second criterion?

7. What is the name of the circuit used to implement the positive feedback network?

8. What is the β of the positive feedback network at the frequency of oscillation?

9. Calculate the minimum value that *R3* can be to keep the circuit oscillating if *R4* is 15k.

10. What might be a problem if *R3* was exactly the value you calculated in the previous question?

11. What type of thermistor could *R4* be replaced with to avoid this problem?

12. Briefly explain how a thermistor in place of *R4* ensures the circuit will oscillate.

13. Briefly explain how a thermistor in place of *R4* prevents the output from clipping severely.

14. The oscillator in Figure 2 is faulty and has stopped oscillating. Measurements of DC voltages around the circuit are shown in Figure 4 below. What component is faulty?

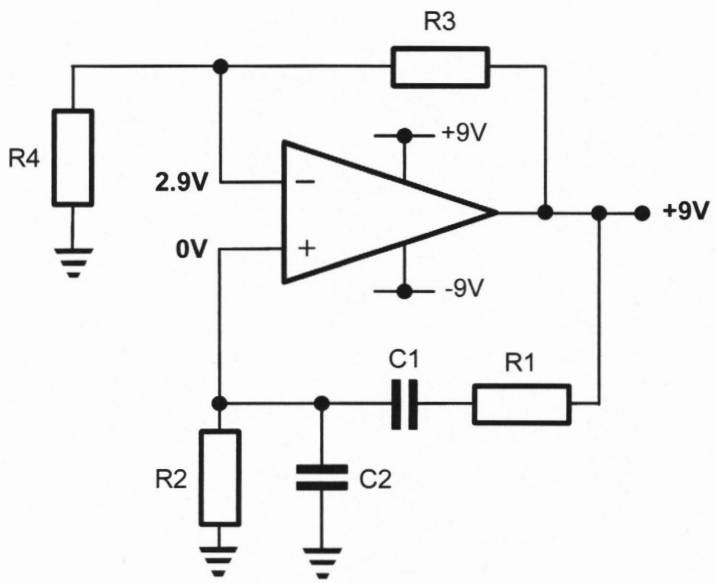

Figure 2

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Student notes

Section 3 The Hartley and Colpitts oscillators 1

Purpose To develop your ability recognise and understand the operation of two classic sinusoidal oscillators implemented using a BJT amplifier and an LC positive feedback network.

Objectives At the end of this section you should be able to:

- Identify the Hartley, Colpitts and Modified Colpitts (or Clapp) oscillators in schematic diagrams
- Predict the output waveshape of the Hartley, Colpitts and Modified Colpitts oscillators given a schematic diagram
- Calculate the frequency of oscillation of the Hartley, Colpitts and Modified Colpitts oscillators given component values
- Explain how Barkhausen's Criteria is satisfied to ensure that the Hartley, Colpitts and Modified Colpitts oscillators start oscillating
- Explain why Barkhausen's Criteria doesn't explain how the Hartley, Colpitts and Modified Colpitts oscillators sustain undistorted sinusoidal oscillation
- Explain why an RF choke is often used in the collector arm of BJT amplifier sinusoidal oscillators
- Use an oscilloscope to practise making measurements in oscillator circuits and to investigate the operation of the Hartley, Colpitts and Modified Colpitts oscillators implemented using a BJT amplifier and an LC positive feedback network

Introduction

Although the Wien-bridge oscillator can produce sinewaves with the lowest distortion figure of most simple sinewave oscillator circuits, its use is restricted to applications below about 1MHz or 2MHz (depending on which text book you read). This frequency is too low for communications equipment such as amateur two-way radio, broadcast FM radio, UHF two-way radio, television and so on. These operate at frequencies from about 27MHz (amateur two-way radio) to hundreds of megahertz (television) and even Gigahertz (mobile phones and radar). At these frequencies the capacitor values in the RC feedback network become too small to have meaningful tolerances.

One of the ways of designing sinusoidal oscillators to operate at high frequencies is to use LC filters in the feedback network. This chapter looks at three LC oscillators (though there are others). They are the *Hartley* oscillator, the *Colpitts* oscillator and the *Modified Colpitts* oscillator. Importantly, all three circuits shown will be implemented using a BJT amplifier rather than an op amp. That's because op amps don't have sufficient bandwidth to permit them to oscillate at the frequencies that are possible for LC oscillators and so they're unlikely to be used.

The Hartley oscillator

Figure 1 shows an example of a Hartley oscillator. This circuit is implemented using the voltage divider baised common emitter BJT amplifier but base bias and/or the common base configuration could be used (see more later this chapter). (Note: The circuit's common has been shown using earth symbols to simplify the drawing so that it's not too cluttered. The common of oscillator circuit's need not be connected to earth.This is done for all circuits in this chapter.)

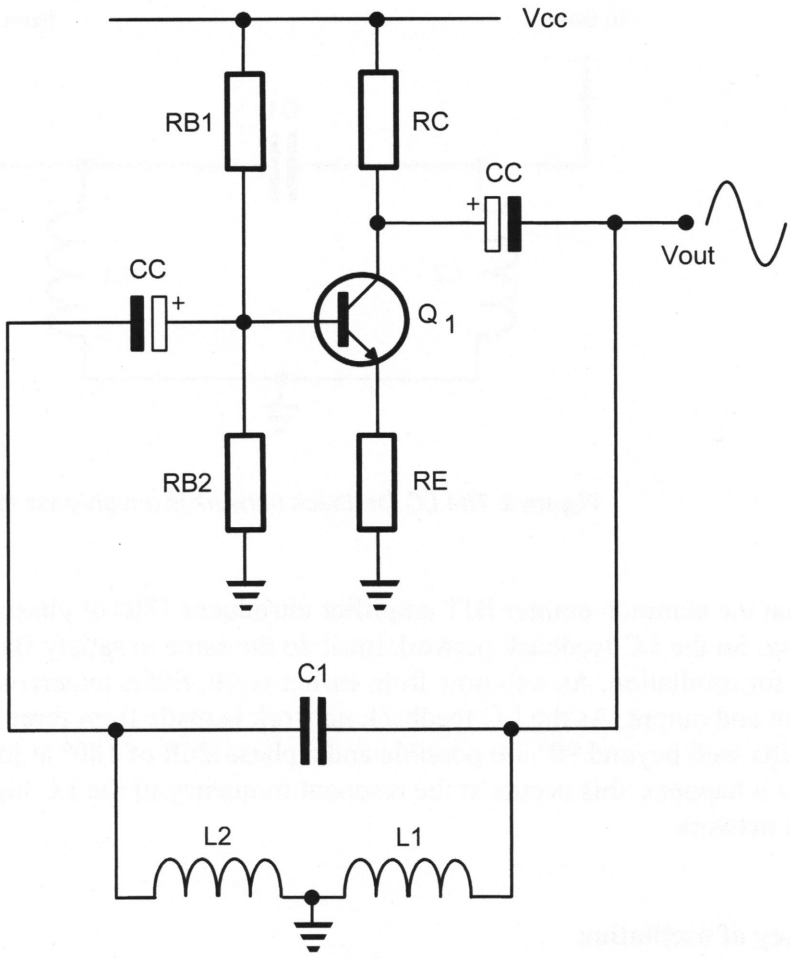

Figure 1 *The Hartley oscillator*

Notice that coupling capacitors are used to connect the BJT amplifier to the positive feedback network. Recall that, from a DC perspective, inductors are a low resistance device. So coupling capacitors are necessary to prevent the feedback network from affecting the amplifier's biasing conditions.

Satisfying Barkhausen's 2nd and 3rd criteria

The circuit's operation can be analysed by thinking of it as being made from two separate circuits; a BJT amplifier that you'll recall introduces 180° of phase shift, and a parallel LC feedback network comprising of *C1* and two inductors *L1* and *L2* (though a tapped-inductor is often used). The feedback network is a filter and this can be more readily seen if the network is redrawn as shown below in Figure 2.

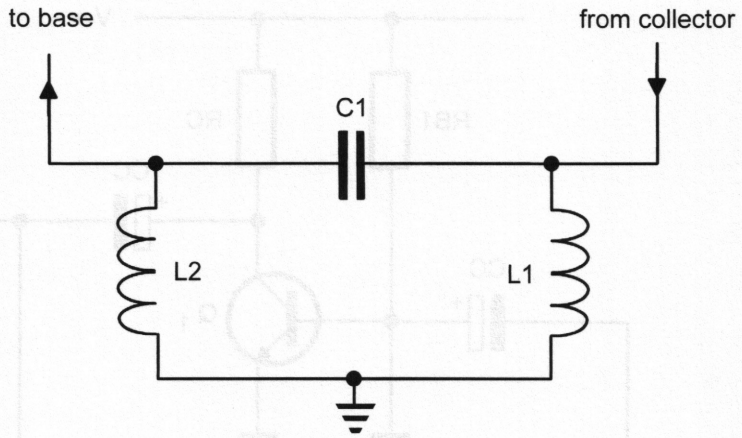

Figure 2 *The LC feedback network is a high-pass filter*

Recall that the common emitter BJT amplifier introduces 180° of phase shift between its input and output. So the LC feedback network must do the same to satisfy Barkhausen's second criterion for oscillation. As we know from earlier work, filters experience phase shifts between their input and output. As the LC feedback network is made from three reactive components, phase shifts well beyond 90° are possible and a phase shift of 180° at just one frequency will occur. As it happens, this occurs at the resonant frequency of the LC high-pass filter used in the feedback network.

Frequency of oscillation

As Barkhausen's second criterion is satisfied at the resonant frequency of the LC combination, the frequency of oscillation can be found using the equation:

$$fo = \frac{1}{2\pi\sqrt{L_T C}}$$

Where L_T is the total inductance of the LC feedback network

To calculate the total inductance in the LC feedback network you simply add the value of the individual inductors. In other words, $L_T = L1 + L2$. However, this equation is only valid when discrete inductors are used.

Practise using the equation by trying the following questions:

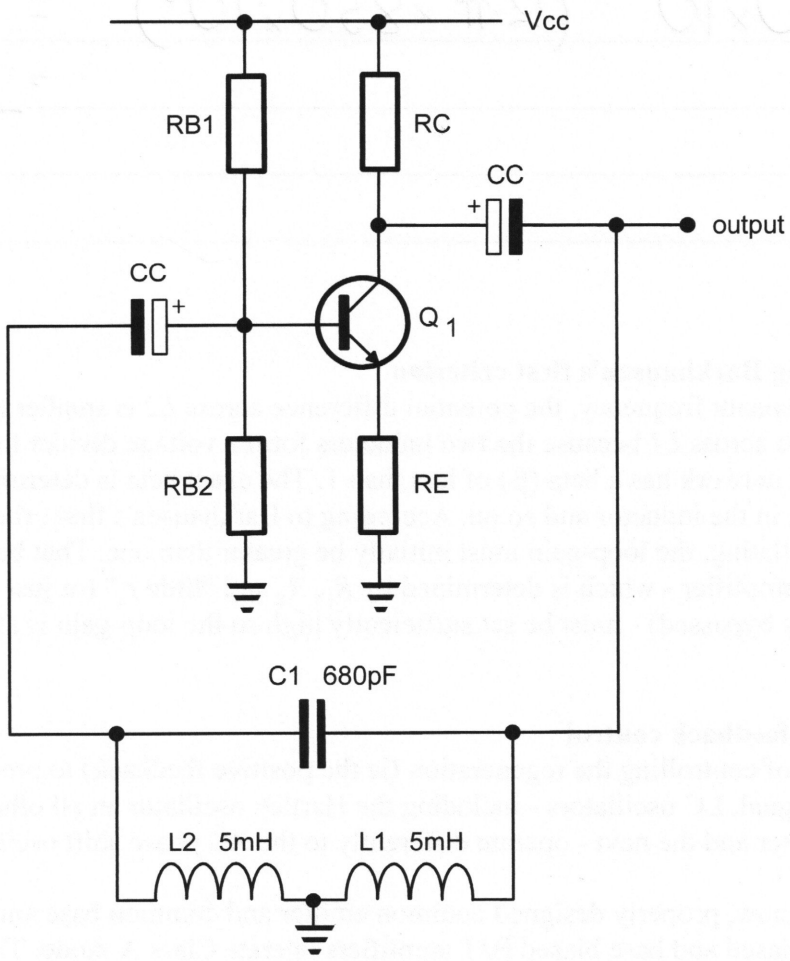

Figure 3

1. Calculate the frequency of oscillation for the circuit in Figure 3.

61 KHz

2. What value of capacitor would make this circuit oscillate at 850kHz?

$$C = \frac{1}{10\times10^{-3}\left(2\pi\times850\times10^{3}\right)^{2}} = 3.5\times10^{-12}$$

$$= 3.5\ pF$$

Satisfying Barkhausen's first criterion

At the resonant frequency, the potential difference across *L2* is smaller than the potential difference across *L1* because the two inductors form a voltage divider to AC voltages. So, the LC feedback network has a beta (β) of less than 1. The exact beta is determined by the number of windings in the inductor and so on. According to Barkhausen's first criterion, for the circuit to start oscillating, the loop-gain must initially be greater than one. That being the case, the gain of the BJT amplifier - which is determined by R_C, R_E and "little r_e" (or just R_C and r_e if the emitter resistor is bypassed) - must be set sufficiently high so the loop-gain is at least 1.

Positive feedback control

In terms of controlling the regeneration (ie the positive feedback) to prevent clipping on the output signal, LC oscillators - including the Hartley oscillator an all other oscillators discussed in this chapter and the next - operate differently to the RC phase shift oscillators.

As you know, properly designed common emitter and common base amplifiers that are voltage divider biased and base biased BJT amplifiers operate Class A mode. That is, the BJT conducts for the whole of the duration of (that is, for 360° of) the output signal. As the circuits in this chapter all use one of these configurations and biasing methods, these oscillators all must operate in Class A mode. But, this is only true at start-up.

To explain, as you know, once oscillation starts, the output voltage's amplitude gets bigger. And, as the output is fed back to the oscillator's input, this must also be true of the BJT amplifier's input voltage and this, in turn, causes the output to get bigger still. But something interesting happens. Once the output voltage becomes sufficiently large, the input voltage also becomes sufficiently large to cause the negative peaks on the amplifier's input to pull the transistor's base voltage (V_B) so low that the transistor can't turn on. This occurs for all of the output signal's positive half cycle and some of its negative half cycle too! In other words, the BJT starts operating in Class C mode where it's only turned on for something less than 180° of the output signal.

The question then becomes, how does the oscillator continue to output a sinewave if the transistor turns off? To understand this, a different way of thinking about the operation of LC oscillators becomes necessary.

First, recall what happens to a parallel LC circuit (often called a "tank" circuit) when a stepped-change in voltage is applied. The arrangement is shown in Figure 4 below.

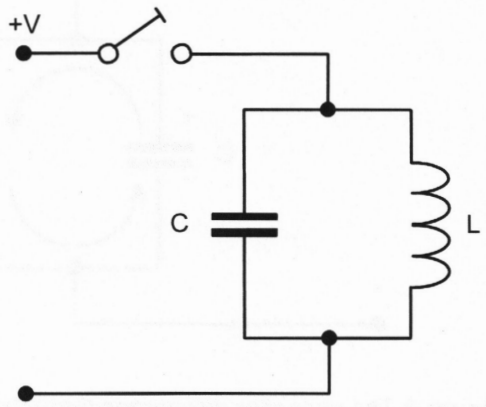

Figure 4 *A parallel LC circuit made from an ideal inductor and capacitor*

When the normally open switch is momentarily closed, current flows via the capacitor and charges it up instantly (see Figure 5).

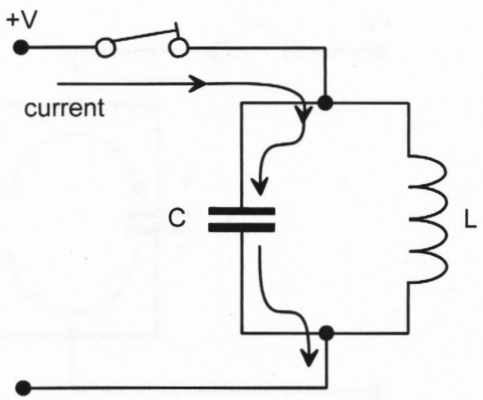

Figure 5 *When the switch is closed current flows through the capacitor and charges it up instantly*

When the switch is released and opens again, the inductor provides a current path that discharges the capacitor (see Figure 6). Importantly, this energises the inductor in the process storing energy as an electromagnetic field about it. In other words, energy is transferred from the capacitor to the inductor.

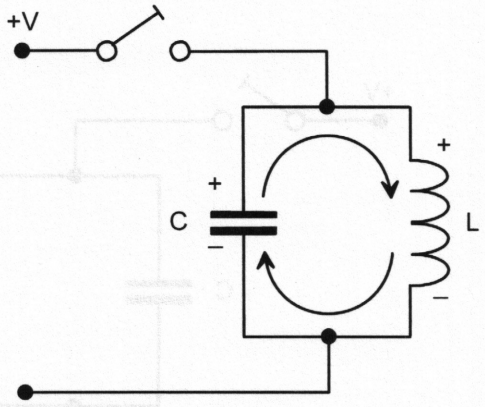

Figure 6 *The capacitor discharges through the inductor*

When the capacitor is fully discharged, the circuit current stops. The capacitor then looks like a short-circuit across the inductor and so its electromagnetic field collapses producing a back EMF and current flows in the reverse direction charging the capacitor back up (see Figure 7). Obviuosly then, energy is transferred from the inductor back to the capacitor.

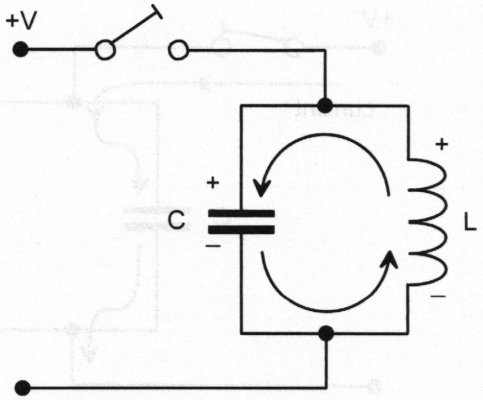

Figure 7 *The collapsing field about the inductor charges the capacitor back up*

When the electromagnetic field has fully collapsed, the capacitor is fully charged. But again the inductor facilitates the discharging the the capacitor and so the process just described repeats. In this way, the circuit moves energy back and forth between the two components bringing to mind the way water in a tank sloshes back and forth if its bumped or moved (hence the name "tank" circuit).

The charge and discharge characteristics of the inductor and capacitor means that the voltage developed across the parallel network while this is going on is a sinewave. If the capacitor and the inductor are ideal, there would be no loss in the sytem and the sinusoidal exchange of energy would continue indefinitely as shown in Figure 8a below. However, as capacitors and inductors are never ideal, they have losses that cause the sinusoidal exchange of energy to decay as shown in Figure 8b.

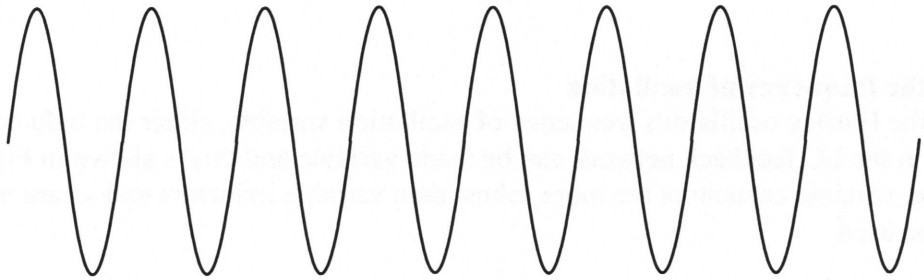

Figure 8a *The sinewave produced by the charging and discharging of the capacitor*

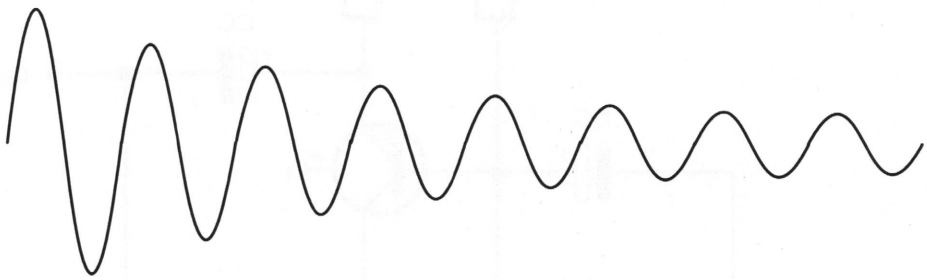

Figure 8b *Losses in the components causes the charging and discharging process to decay*

Now, suppose that the switch is closed again as the damped oscillation approaches its next positive peak. The capacitor, which is being charged by the de-energising inductor, is also charged by the voltage source, topping it up to maximum again. This means that the positive peak voltage of the second cycle would be the same as the first. And, if this happened on every subsequent cycle of the damped oscillations, then they wouldn't decay at all.

Importantly, something like this is happening in the Hartley oscillator's positive feedback network. As already mentioned, the signal on the amplifier's input turns the BJT off for over half of every cycle of the output waveform. But, for a time during each half cycle of the oscillation, the transistor is turned on again, topping-up the tank circuit with energy to keep the output from decaying.

So, how does this work to prevent the output from becoming clipped? For a start, once the BJT starts operating in Class C mode then, in terms of sustaining the oscillation, Barkhausen's Criteria no-longer explains the circuit's operation and so the whole issue of a loop gain of greater than one causing runaway regeneration is no-longer applicable.

Second, there's a relationship between the output voltage and the duration of the BJT's on time (proof of which is not shown here because it's a little complicated and ultimately doesn't help with trouble-shooting when the oscillator is faulty). But the issue can be understood this way. The amplifier initially operates in Class A mode until the oscillator's output voltage is sufficiently large to for it switch to Class C mode. As the output voltage continues to get bigger, the BJT is turned off for longer and so it's turned on for less time and so pumps less energy into the tank circuit. So, provided the BJT amplifier's biasing is optimised (a design issue), the arrangement regulates itself at a particular output voltage below that which would experence clipping.

Varying the frequency of oscillation

To make the Hartley oscillator's frequency of oscillation variable, either the inductor or the capacitor in the LC feedback network can be made variable and this is shown in Figure 9 below. In practice, variable capacitors are more robust than variable inductors and so are much more likely to be used.

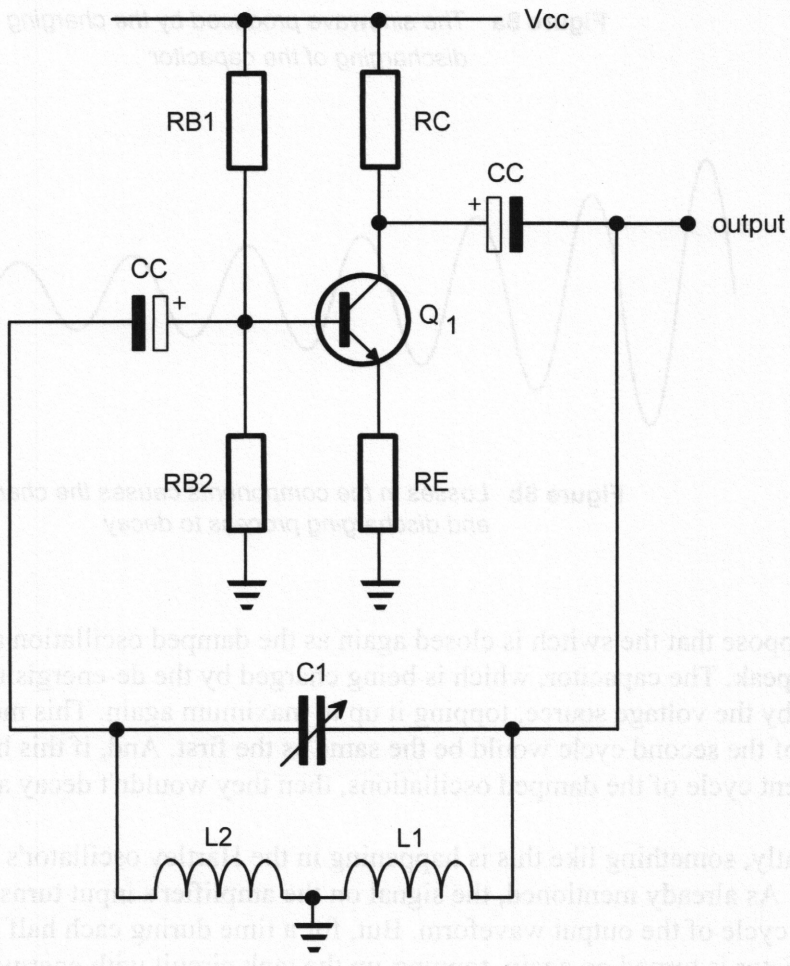

Figure 9 *A Hartley oscillator with variable output frequency*

Other Hartley oscillator designs

The Hartley oscillator can be implemented using BJTs and FETs operated in either the common emmiter/source or common base/gate configurations and using voltage divider biasing or base/self bias (depending on the device). As an example, Figure 10 below shows the Hartley oscillator made using a voltage divider biased common base BJT amplifier.

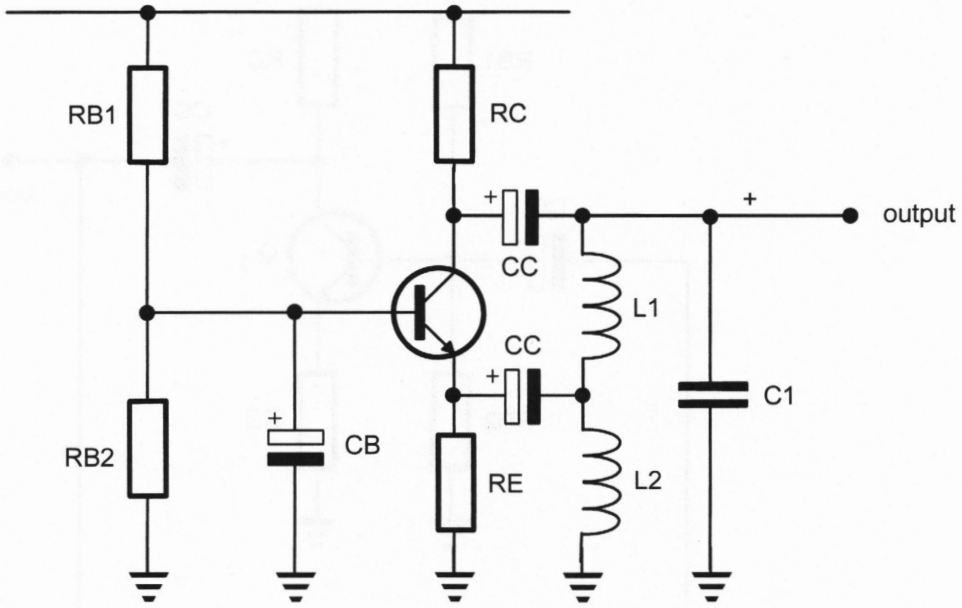

Figure 10 *Hartley oscillator designed from a voltage divider biased, common base BJT amplifier*

If you remember your BJT amplifier theory, you'll recall that the input-output phase relationship of the common base BJT configuration is 0°. Conveniently, the positive feedback network's connection to the amplifier (which, if you look closely, is different to the circuit in Figure 1) introduces 0° of phase shift at the LC circuit's resonant frequency so the frequency of oscillation is also calculated using the equation on page 3-4.

As already mentioned, although the Hartley oscillator can be implemented using an op amp, it is not common to do so. LC oscillator circuits are typically used for high frequency applications which means they are often designed to operate at frequencies beyond the GBWP of most op amps. In fact, in high frequency radio applications, you're more likely to see the common base BJT configuration being used because of its wider bandwidth compared to the common emitter configuration.

Generally speaking, Hartley oscillators do not produce sinewaves as pure as other oscillator designs (especially the Wien-bridge). However, the output voltage level remains fairly constant over a range of frequencies which is particularly important for variable frequency oscillators.

The Colpitts Oscillator

Figure 11 shows an example of a Colpitts oscillator. This circuit is implemented using the voltage divider baised common emitter BJT amplifier but base bias and/or the common base configuration could be used (see more later this chapter).

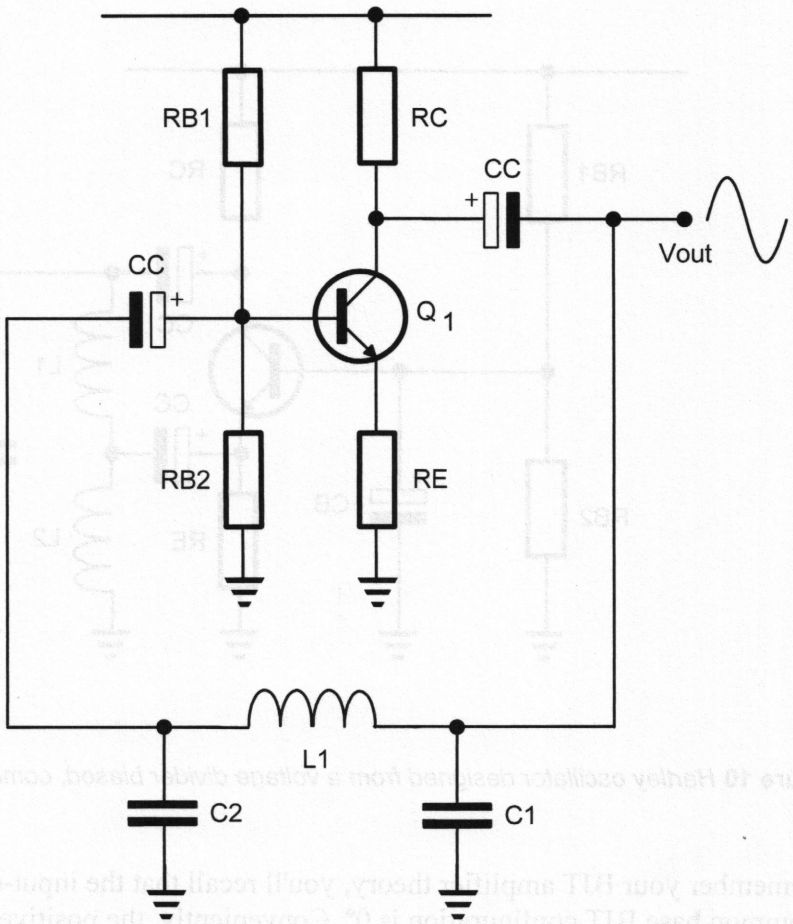

Figure 11 *The Colpitts oscillator*

Notice that coupling capacitors are used to connect the BJT amplifier to the positive feedback network. Recall that, from a DC perspective, inductors are a low resistance device. So coupling capacitors are necessary to prevent the feedback network from affecting the amplifier's biasing conditions.

Satisfying Barkhausen's 2nd and 3rd criteria

The circuit's operation is almost identical to the Hartley oscillator. The Colpitts oscillator consists of two separate circuits: a voltage divider biased, common emitter BJT amplifier which introduces 180° of phase shift between its input and output; and a parallel LC feedback network comprising of *C1*, *L1* and *C2*. The LC feedback network is actually a three element filter which introduces another 180° of phase shift but only at one frequency - the LC combination's resonant frequency.

Frequency of oscillation

As Barkhausen's second criterion is satisfied at the resonant frequency of the LC combination, the frequency of oscillation can be found using the equation:

$$fo = \frac{1}{2\pi\sqrt{LC_T}}$$

Where C_T is the total capacitance of the LC feedback network

Importantly, to calculate the total capacitance in the LC feedback network you must combine the capacitor values as though they are in series. This means that the total capacitance is found by using the equation: $C_T = \frac{1}{\frac{1}{C1}+\frac{1}{C2}}$.

This might seem odd because, at a glance, *C1* and *C2* look as though they're connected in parallel with each other and so the total capacitance should be calculated differently. However, in terms of how they are connected to the inductor they are in series not in parallel. To appreciate this, consider the circuit in Figure 12 which shows a different way of drawing exactly the same connections to earth (or more likely common) for the capacitors in the LC feedback network.

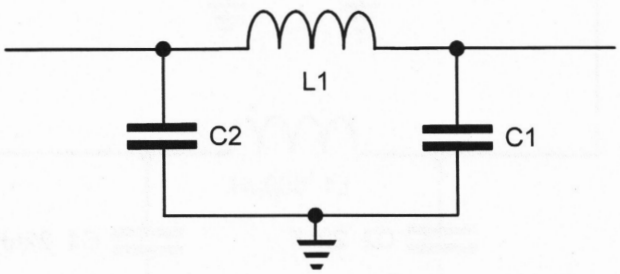

Figure 12 *A different way of drawing the LC feedback network of the Colpitts oscillator*

If we now move the capacitors' position without changing the circuit, we can get Figure 13 below.

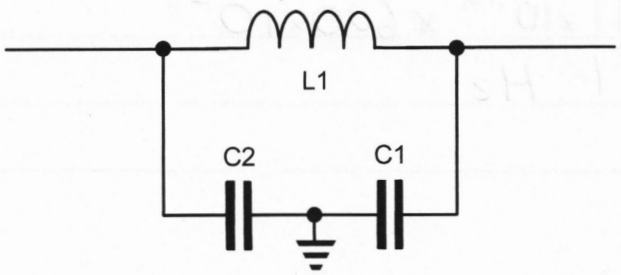

Figure 13

Drawn this way we can see that earth (or common) is acting as a wire connecting *C1* and *C2*. So, they're actually in series with each other and together they are in parallel with the inductor.

Practise using the equation by trying the following questions:

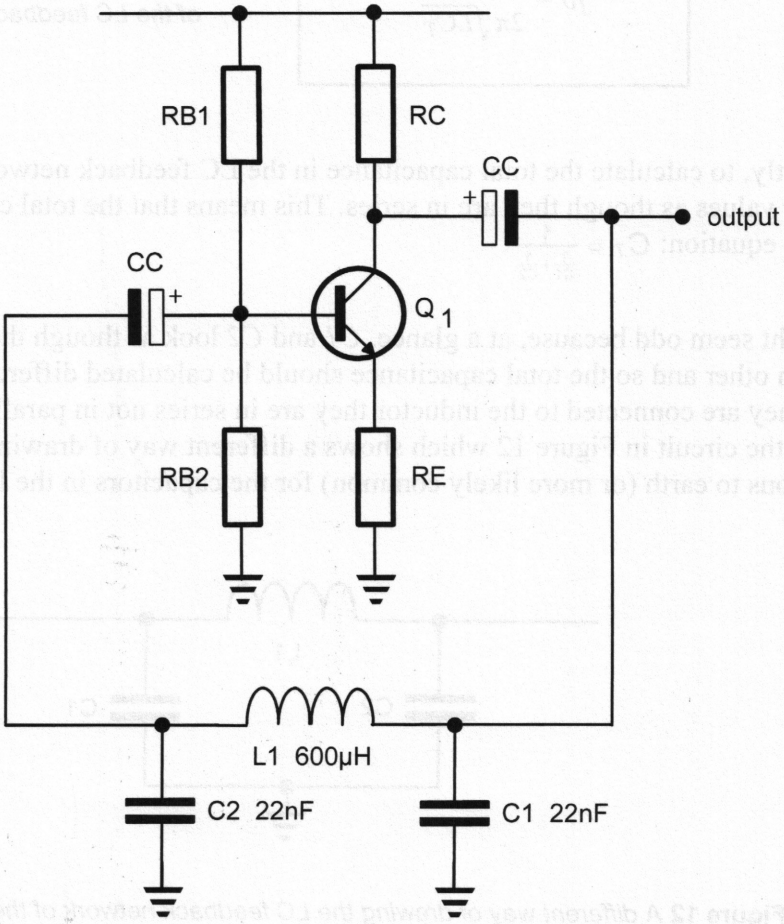

Figure 14

1. Calculate the frequency of oscillation for the circuit in Figure 14.

$f_o = \frac{1}{2\pi \times \sqrt{11 \times 10^{-9} \times 600 \times 10^{-6}}}$

$= 61951 \text{ Hz}$

2. What value of inductor would make this circuit oscillate at 30kHz?

$$L = \frac{1}{(2\pi \times 30\,KHz)^2 \times 11nF} = 2.56mH$$

Satisfying Barkhausen's 1st criterion

At the resonant frequency, the potential difference across *C2* is one tenth of the potential difference across *C1*. So, the LC feedback network has a beta (β) of $\frac{1}{10}$ or 0.1. According to Barkhausen's first criterion, for the circuit to start oscillating, the loop-gain must be equal to or greater than one. That being the case, the gain of the BJT amplifier - which is determined by R_C, R_E and r_e (or just R_C and r_e if the emitter resistor is bypassed) - must be programmed so that it is at least 10.

Positive feedback control

Control over the positive feedback works in exactly the same manner as for the Hartley oscillator so the explanation is not repeated for this circuit.

Varying the frequency of oscillation

To make the Colpitts oscillator's frequency of oscillation variable either the inductor or one or both of the capacitors in the LC feedback network are made variable. Either method can be used but making just one of the capacitors variable is a little problematic. As already mentioned, the beta (β) of the positive feedback network is 0.1 and this is true for any value capacitor provided *C1* and *C2* are the same as each other. However, changing the value of just one of the capacitors to change the frequency of oscillation would also change the β of the network. Doing so runs the risk of lowering the loop-gain below one and preventing oscillation.

To avoid this problem both capacitors must be changed by the same amount at the same time. The only way to do this is to make *C1* and *C2 ganged* variable capacitors (see Figure 15 on the next page) where one control varies the value of two capacitors at once. However, this increases the cost because ganged variable capacitors are more expensive to make than ordinary variable capacitors.

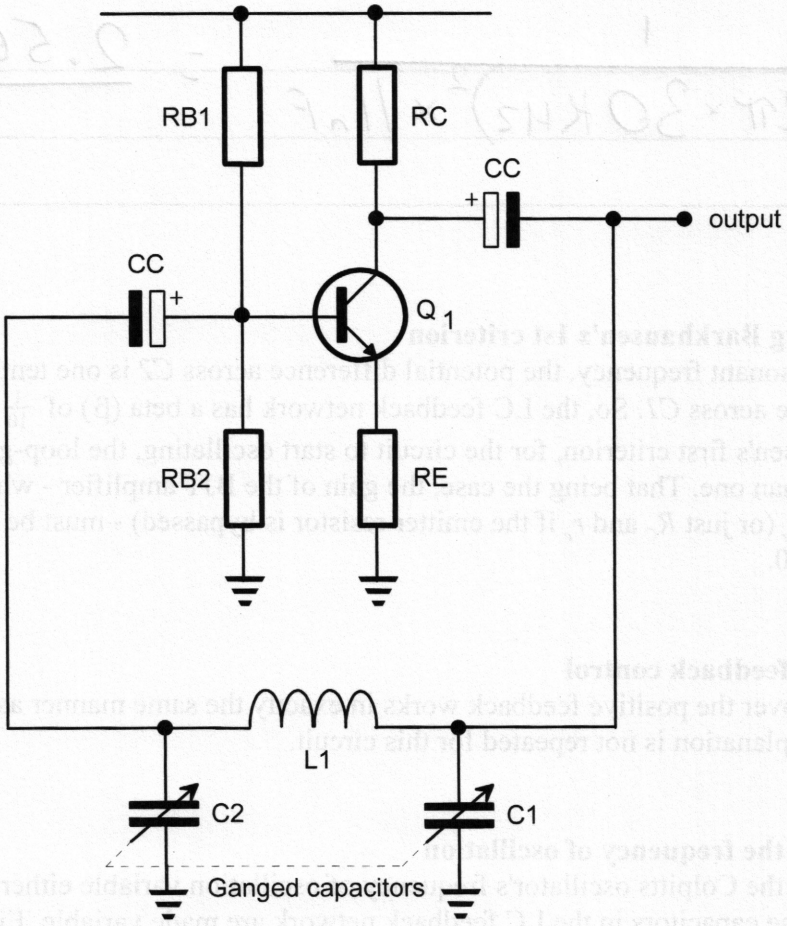

Figure 15 *A variable frequency Colpitts oscillator using ganged capacitors*

Other Colpitts oscillator designs

As with the Hartley oscillator, the Colpitts oscillator can be made using BJTs and FETs operated in either the common emmiter/source or common base/gate configurations using one of a couple of biasing methods. As an example, Figure 16 below shows the Colpitts oscillator made using a common base PNP BJT amplifier.

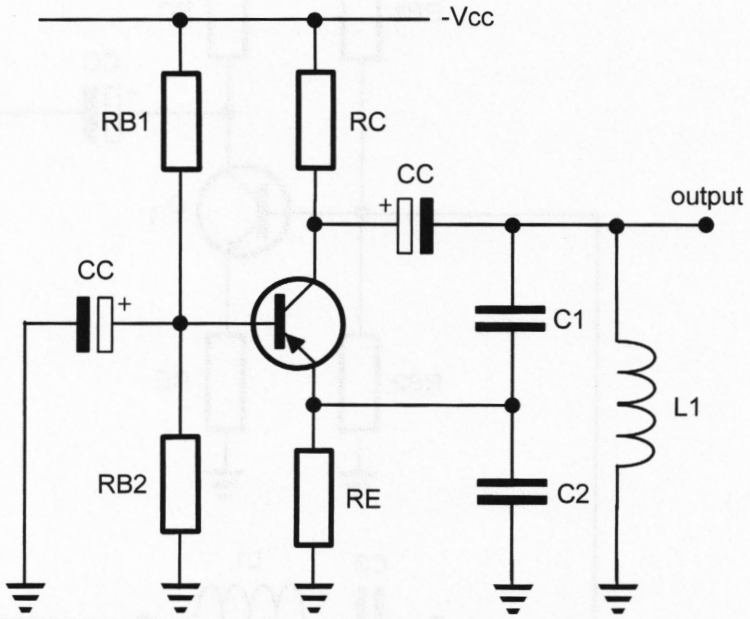

Figure 16 *Colpitts oscillator designed from a voltage divider biased, common base PNP BJT amplifier*

Like the common base Hartley oscillator, this circuit satsifies Barkhausen's Criteria slightly differently to the common emitter BJT amplifier and has been explained already under Figure 10 on page 3-11. And for reasons also discussed on that page, the Colpitts oscillator can be implemented using an op amp but this is unlikely.

Generally speaking, the Colpitts oscillator produces a more pure sinewave than the Hartley oscillator but its output level can vary with changes in frequency.

The Modified Colpitts (or Clapp) oscillator

Another commonly used oscillator is the *Modified Colpitts* oscillator (also often known as the *Clapp* oscillator). The circuit is shown in Figure 17.

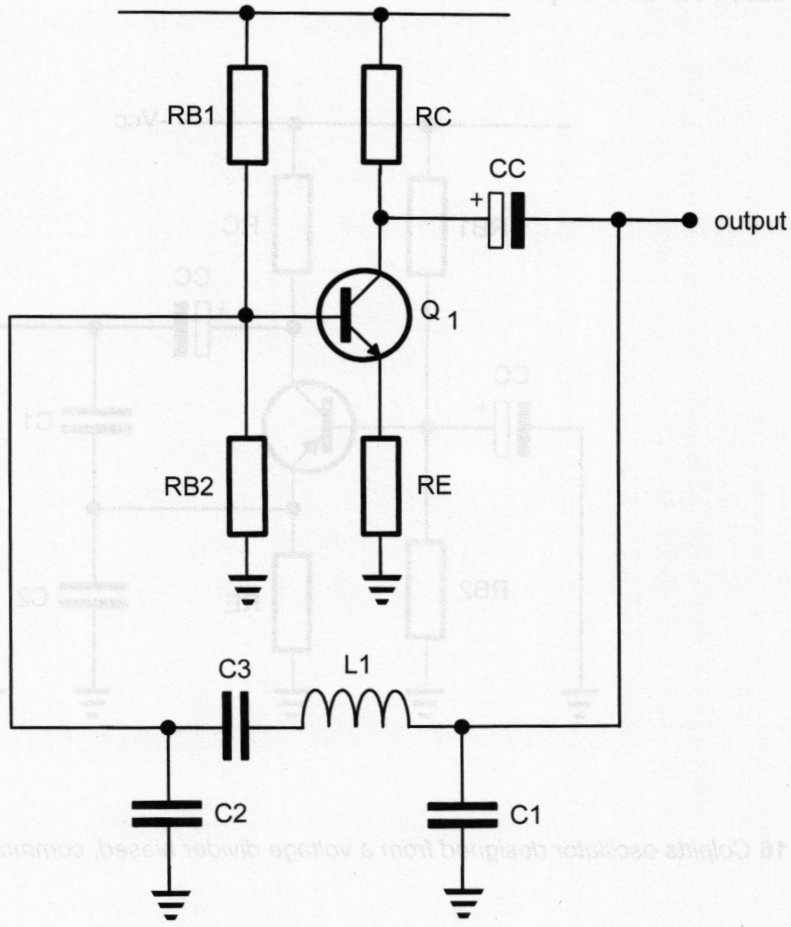

Figure 17 *The Modified Colpitts (or Clapp) oscillator*

It can be seen from this drawing that the why this oscillator gets its name. The circuit is basically the same as the Colpitts oscillator but with the inclusion of a capacitor in series with the inductor in the LC feedback network (making it a band-pass filter rather than a low-pass filter). This oscillator's operation is the same as the Colpitts so it is not explained again here.

Although the Colpitts and Modified Colpitts oscillators operate in basically the same way, there is an important difference between the two circuits. Calculating the frequency of oscillation for the Modified Colpitts oscillator can be a little more involved because there are now three capacitors in the network. However, if the values of *C1* and *C2* are made much larger than *C3* their effect on the total capacitance is minimal and can be ignored. That being the case, the frequency of oscillation can be found using the equation:

$$fo = \frac{1}{2\pi\sqrt{LC_3}}$$

Designing the Modified Colpitts oscillator this way has an advantage. If the effect of *C1* and *C2* on the frequency of oscillation is negligible then, to make the frequency of oscillation variable, only *C3* need be made variable. This saves on the cost of using a ganged capacitor for *C1* and *C2* which is required for the Colpitts oscillator with a variable output frequency.

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Isolating the LC feedback network from the supply rail

All of the oscillators discussed in this chapter are highly likely to be just one block in an electronics system. This means that the supply rail used by the oscillator circuit is likely to be shared with other circuits in the system. This can cause a problem for the oscillator because other components in these circuits can effect the LC feedback network via the collector resistor and, in turn, affect the frequency of oscillation in the process. Conversely, the oscillator's output can leak into the supply rail introducing a high frequency ripple. To minimise the risk of both of these problems, an RF choke (inductor) is used instead of a collector resistor and this is shown in Figure 18 on a Hartley oscillator.

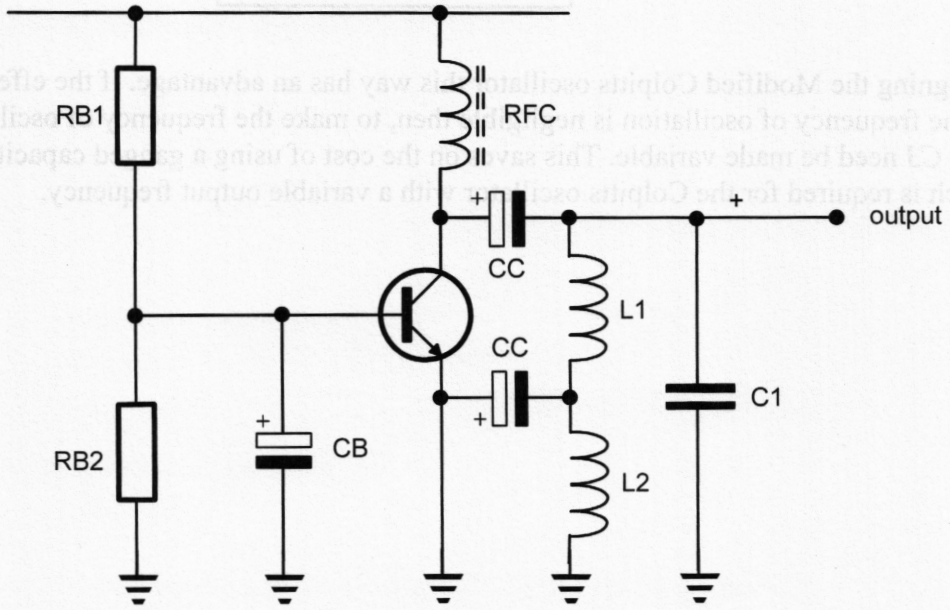

Figure 18 *A Hartley oscillator with an RF choke in the collector circuit instead of a resistor*

Recall that inductors can look like a higher impedance to AC signals than their DC resistance. Usually the RFC's value is chosen so that, at the frequency of oscillation, the impedance is so high that the path from BJT's collector to the supply rail looks like an open-circuit. This effectively disconnects the circuit from the power supply from an AC perspective. Although this use of an RFC is demonstrated on a Hartley oscillator in the Figure above, it is used for Colpitts and Modified Colpitts oscillators also.

Importantly, to avoid the RFC's value affecting the circuit's frequency of oscillation, it should be a value that is at least ten times the value of the inductors in the positive feedback path.

Identifying the Hartley, Colpitts and Modified Colpitts oscillators in circuit

In busy schematic diagrams of communications equipment it can be difficult for the novice to identify oscillator circuits and determine whether they are either the Hartley, Colpitts or Modified Colpitts oscillator. These circuits can easily be confused with active band-pass and band-stop filters which are also common in communications equipment. Furthermore, the oscillators can be made from a variety of amplifying devices (BJTs, JFETs, MOSFETs) and in a variety of configurations (common base/gate and common emitter/source) using one of a couple of biasing methods (base/self bias and voltage divider bias). Other components such as an RF choke used to isolate the supply rail can confuse the matter more.

As a starting point, you need to look for a tank circuit. The basic design of a tank circuit is an inductor in parallel with a capacitor, but remember that for the Hartley, Colpitts and Modified Colpitts oscillators they can involve either centre-tapped inductor or a "tapped capacitor". (Note: the term "tapped capacitor" is a figurative term for the fact that two series capacitors are used with a feed to another part of the circuit taken from the point where they are connected.)

Once you have found the tank circuit, you then work out whether the circuit is an active filter or an oscillator by examining how the tank circuit is connected to the BJT/FET. If it is connected to only one of the pin of the BJT/FET then the circuit likely to be an active band-pass or band-stop filter (and so the other side of the tank circuit is probably connected to either the supply rail or ground/common). If the tank circuit is connected between two of the pins on the BJT/FET then it is probably part of an oscillator.

If the tank circuit contains a tapped-inductor then it is probably a Hartley oscillator. If not, then it'll probably be either a Colpitts or a Modified Colpitts oscillator. To distinguish between the Colpitts and the Modified Colpitts oscillators, look at the inductor and see if there is a third capacitor connected in series with it. If not, the oscillator is probably a Colpitts. If there is, the oscillator is probably a Modified Colpitts.

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Student notes

Skill practice 3

Practise measuring key voltages in LC oscillators using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you'll be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Emona Trainer
- decade box
- DMM
- BC547 transistor
- 2.5mH choke
- 8.2mH choke
- 56kΩ ¼W resistor
- two 100nF capacitors four
- 22nF capacitors one 3.3nF
- capacitor BNC to
- alligator-clip lead hook-up
- wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1.

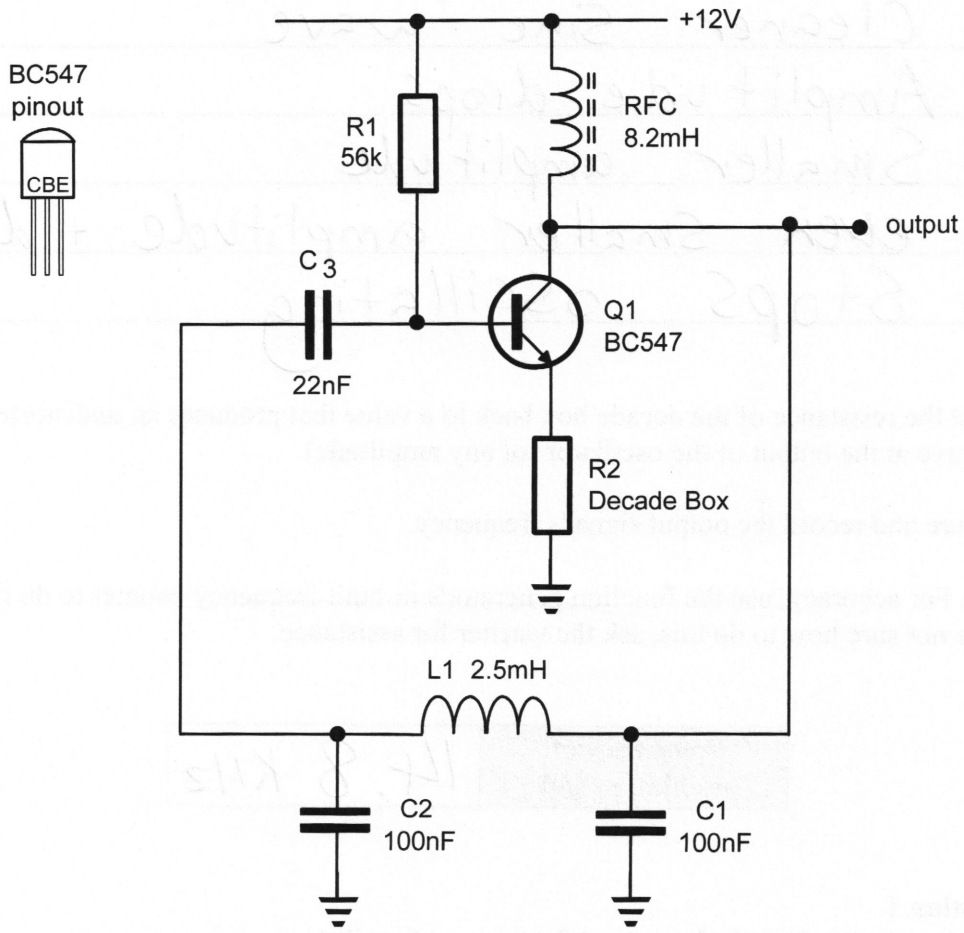

Figure 1

4. Adjust the decade box to 0Ω.

5. Turn on the power supply to the circuit.

6. Connect one of the CRO's inputs to the circuit's output and adjust it accordingly.

   Self-check: If your circuit is oscillating you should see a sinewave. If it not, check your wiring and test the transistor before calling the teacher for assistance.

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7. Increase the resistance of the decade box in 100Ω steps and record what happens to the shape of the output signal with each increase. Continue until the oscillator stops oscillating.

100Ω A little distorted sine wave

200Ω Cleaner sine wave

300Ω Amplitude drops

400Ω Smaller amplitude

500Ω even smaller amplitude + distortion

600Ω Stops oscillating

8. Adjust the resistance of the decade box back to a value that produces an undistorted sinewave at the output of the oscillator (of any amplitude).

9. Measure and record the output signal's frequency.

Note: For accuracy, use the function generator's in-built frequency counter to do this. If you're not sure how to do this, ask the teacher for assistance.

Frequency of oscillation (*fo*)	14.8 KHz

Question 1
Calculate the oscillator's theoretical frequency of oscillation.

$$C_{eq} = \frac{(100\,nF)(100\,nF)}{100\,nF + 100\,nF} = 50\,nF$$

Question 2
Compare the theoretical frequency of oscillation with the measured value in step 8. Are they reasonably close? What might account for any differences?

$$f_o = \frac{1}{2\pi\sqrt{(2.5\times10^{-3})\times(50\times10^{-9})}} = 14.2\,kHz$$

Fairly close within 10%

10. Turn off the power supply to the circuit.

11. Replace capacitors *C1* and *C2* with 22nF capacitors.

12. Turn on the power supply.

13. Observe the oscillator's output using the CRO to check that it's oscillating and the output voltage is an undistorted sinewave.

    Note: If necessary, increase the decade box's resistance to reduce any distortion.

14. Measure and record the output signal's frequency.

Frequency of oscillation (*fo*)	32.6 KHz

Question 3
Calculate the oscillator's new theoretical frequency of oscillation. Compare this value with the measured frequency in Step 14.

$f_o = \frac{1}{2\pi\sqrt{(2.5\times10^{-3})\times(11\times10^{-9})}} = 30.3\,KHz$

Question 4
What is the general relationship between the values of *C1* and *C2* and the frequency of oscillation?

fairly close but just outside 10%
$C_1 + C_2$ increase → frequency decrease
Oscillation is inversely proportional.

The teacher needs to check your work at this point...

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15. Turn off the power supply to the circuit.

16. Adjust the resistance of the decade box to 0Ω.

17. Change the circuit to a Modified Colpitts oscillator as shown in Figure 2.

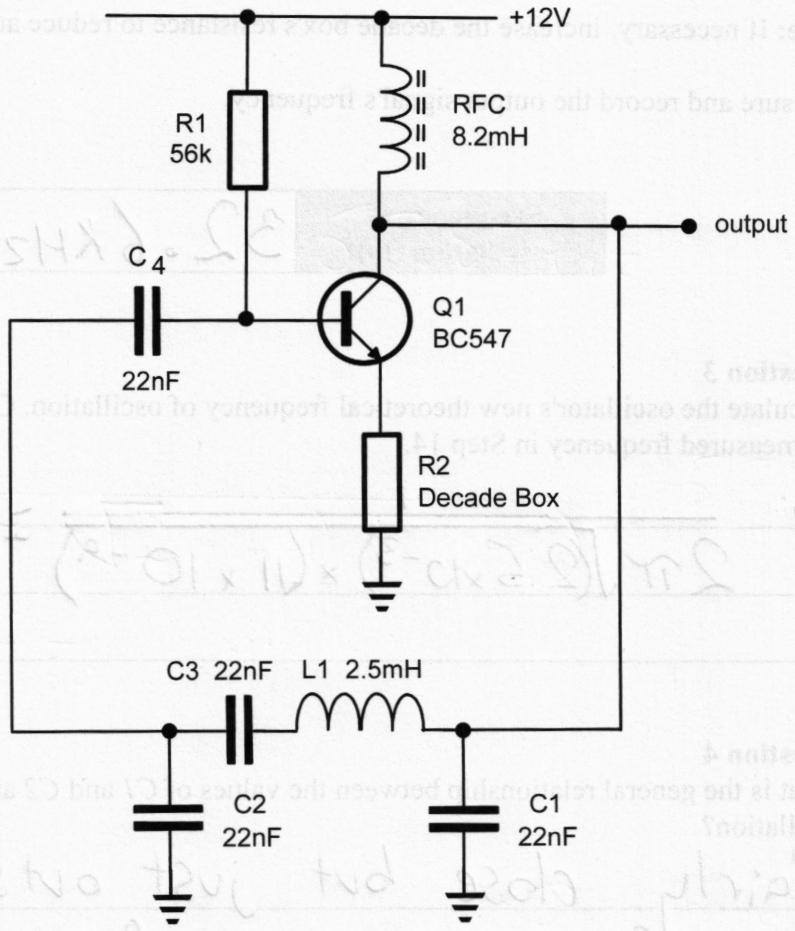

Figure 2

18. Turn on the power supply to the circuit.

19. Observe the oscillator's output using the CRO to check that it's oscillating.

20. Increase the resistance of the decade box until the output is an undistorted sinewave.

    Note: If necessary, increase the decade box's resistance to reduce any distortion.

21. Measure and record the output signal's frequency.

Frequency of oscillation (*fo*)	38.8 KHz

Question 5
Calculate the oscillator's theoretical frequency of oscillation using: $fo = \frac{1}{2\pi\sqrt{LC_3}}$.

$fo = \frac{1}{2\pi \times \sqrt{(2.5mH) \times (22nF)}} = 21.5\,KHz$

Question 6
Compare the theoretical frequency of oscillation with the measured value in Step 21. Why are they not as close as the measured and calculated frequencies for the Colpitts oscillator?
Tip: I've tricked you into doing something wrong - Can you work out what it is?

Its a clapp oscillator. Resonance is not just C3, its series combination of C3 with equivalent capacitance of C_1+C_2. Tank is only 7.3nF

The teacher needs to check your work at this point...

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22. Turn off the power supply to the circuit.

23. Replace capacitor *C3* a 3.3nF capacitor.

24. Replace capacitors *C1* and *C2* with 100nF capacitors.

25. Turn on the power supply.

26. Observe the oscillator's output using the CRO to check that it's oscillating and the output voltage is an undistorted sinewave.

27. Measure and record the output signal's frequency.

Frequency of oscillation (fo)	57.87 KHz

Question 7
Calculate the oscillator's theoretical frequency of oscillation using: $fo = \frac{1}{2\pi\sqrt{LC_3}}$.

$$fo = \frac{1}{2\pi\sqrt{(2.5mH)(3.096nF}} = 57.2\,KHz$$

$$C_{TANK} = \left(\frac{1}{3.3} + \frac{1}{50}\right)^{-1} = 3.096nF$$

Question 8
Compare the theoretical frequency of oscillation with the measured value in Step 27. Why are they much closer than the measured and calculated frequencies in Step 21 and Question 5?

C1 and C2 are huge (50nF combined) CTANK ≈ C3, so even using 3.3nF brings us close (55.4 KHz). C3 is much smaller than effective capacitance (C1+C2). Total tank is aprox. C3

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 14 refer to the circuit in Figure 1

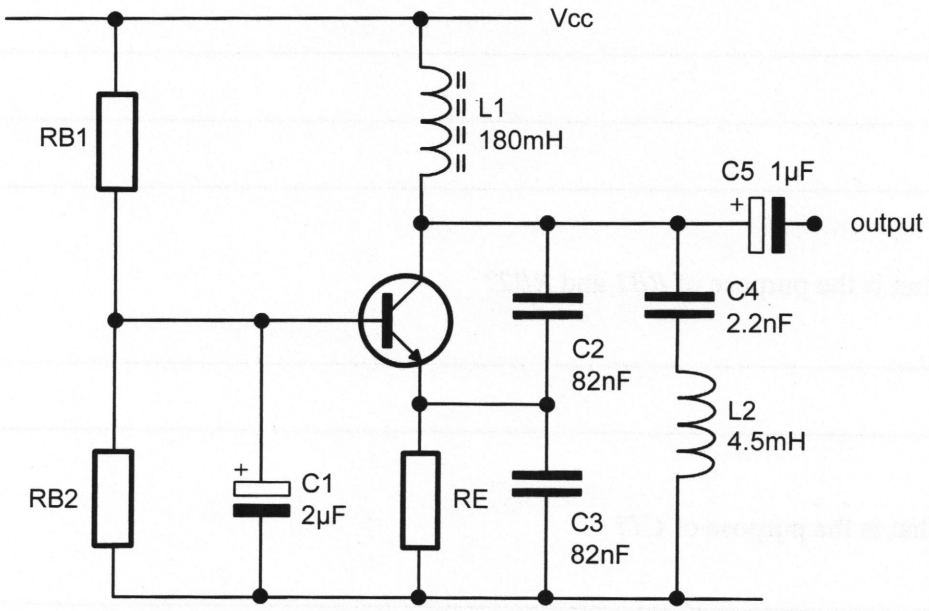

Figure 1

1. What is the name of this oscillator?

2. What waveform would you expect to see on the output?

3. What BJT amplifier configuration is used?

4. Which components form the positive feedback network?

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5. What is the phase shift of the LC feedback network at the frequency of oscillation?

6. Will the voltage at the output of the LC feedback network be smaller or bigger than the circuit's output? Explain your answer.

7. What is the purpose of *RB1* and *RB2*?

8. What is the purpose of *C1*?

9. What is the purpose of *C5*?

10. What is the purpose of *L1*?

11. Calculate the oscillator's theoretical output frequency.

12. Why can the capacitors *C1* and *C2* be ignored when calculating this frequency?

13. In what way is this circuit different to the Colpitts oscillator?

14. What is the most practical modification that you could make to make the oscillator's frequency variable?

Question 15 to 21 refer to the circuit of Figure 2

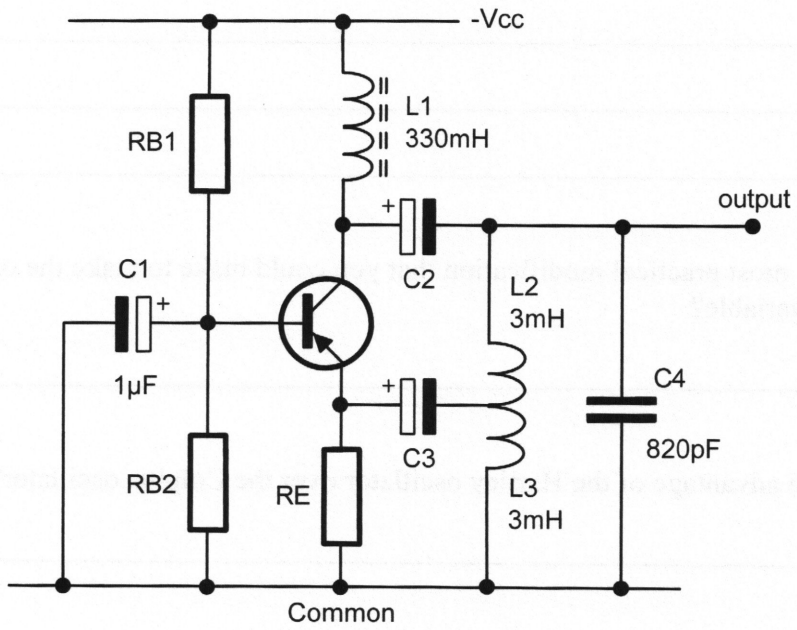

Figure 2

15. What is the name of this oscillator?

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16. What waveform would you expect to see on the output?

17. What BJT amplifier configuration is used?

18. Which components form the positive feedback network?

19. What is the phase shift of the LC feedback network at the frequency of oscillation?

20. Calculate the oscillator's theoretical output frequency.

21. What is the most practical modification that you could make to make the oscillator's output frequency variable?

22. What is one advantage of the Hartley oscillator over the Colpitts oscillator?

23. What is one advantage of the Colpitts oscillator over the Hartley oscillator?

Section 4 The Hartley and Colpitts oscillators 2

Purpose To develop your ability to fault-find the Hartley, Colpitts and Modified Colpitts oscillators implemented using a BJT amplifier and both the LC and cyrstal-controlled positive feedback networks.

Objectives At the end of this section you should be able to:

- List the advantages of implementing oscillators using a quartz crystal as a substitute for the series reactive component in the positive feedback network of LC oscillators
- Describe the frequency versus impedance performance of quartz crystals
- State which resonant frequency is usually specified as a quartz crystal's operating frequency
- Identify the crystal-controlled Hartley, Colpitts and Modified Colpitts oscillators in a schematic diagram
- Explain the operation of the crystal-controlled Hartley, Colpitts and Modified Colpitts oscillators
- Predict the output waveshape of crystal-controlled Hartley, Colpitts and Modified Colpitts oscillators given a schematic diagram
- Predict the frequency of oscillation of the crystal-controlled Hartley, Colpitts and Modified Colpitts oscillators
- Explain how to test a quartz crystal to determine whether it is functioning and to identify it series and parallel mode resonant frequencies
- List the likely faults that can occur in the Hartley, Colpitts and Modified Colpitts oscillators
- Describe the effects of these faults on the performance of the Hartley, Colpitts and Modified Colpitts oscillators
- Explain the basic concept of a *voltage-controlled oscillator* (VCO)
- Explain the terms *sensitivity* and *linearity* in terms of VCO operation
- Recognise the schematic symbol of varicap diodes and explain their operation
- Explain the operation of the Modified Colpitts oscillator adapted to implement a VCO
- Use an oscilloscope to practise making measurements in oscillator circuits and to verify VCO operation and measure sensitivity and linearity

Introduction

Most LC oscillators can be implemented using a quartz crystal as a substitute for either the inductor or capacitor in the feedback network of the Colpitts and Hartley oscillators (respectively). This chapter introduces you to the operation of quartz crystals in an AC circuit and then how they can be used in the Hartley, Colpitts and Modified Colpitts oscillators. After that, fault-finding these three oscillator circuits is discussed. Finally, you'll learn about the *voltage-controlled oscillator* (VCO) and how the Modified Colpitts oscillator is perfectly suited to implementing a VCO.

Quartz crystals

As already mentioned, most LC oscillators can be implemented using a quartz crystal. Importantly, when this is done, the crystal sets the oscillator's frequency of oscillation. There are several advantages for using crystals to do so.

- Improved frequency stability (a "drift" of as little as 1ppm)
- Precise frequency setting

Implementing oscillators using quartz crystals is so widely done these days that it's important for you to learn a little about them.

Schematic symbol

Figure 1 shows the schematic symbol of a crystal.

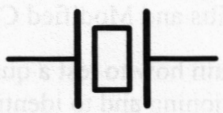

Figure 1 *Schematic symbol of a crystal*

What is a crystal?

There is nothing "magic" about crystals. They're simply a solid material (either a chemical element, compound or mixture) that formed during cooling from a liquid. They're different to other materials in that, on solidification, the atoms or molecules formed a regularly repeating internal arrangement. Quartz is the most common naturally occurring crystal and is the most common type used in electronic circuits.

Like most (if not all) things, quartz crystals exhibit resonance. In fact, quartz crystals have two resonant frequencies. At one frequency, the conduct more current than at any other frequency. At a second frequency, they conduct less current than at any other frequency.

If the performance of quartz crystals is graphed in terms of frequency versus impedance (rather than current) they all have a response like the graph in Figure 2 below. The crystal's physical size and shape determines the two frequencies at which resonance occurs.

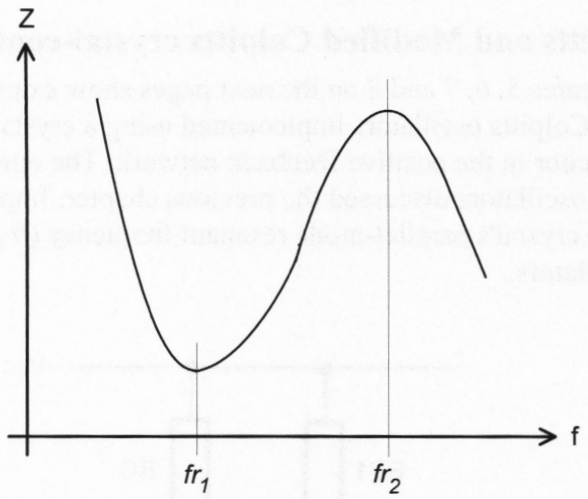

Figure 2 *The response of frequency versus impedance of a quartz crystal*

Quartz crystal equivalent circuit

From an electronics point of view, quartz crystals have the same frequency versus impedance characteristic as the circuit shown in Figure 3 below.

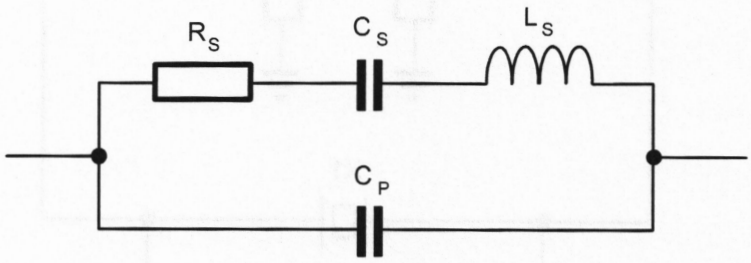

Figure 3 *Quartz crystal equivalent circuit*

Importantly, the effective capacitance of C_S and C_P are different to each other with C_S being much bigger.

The circuit's first resonant frequency (fr_1) occurs when C_P looks like an open-circuit and the reactances of L_s and C_s are equal and opposite. For this reason, the fr_1 of a crystal is known as the *series mode* resonance.

The circuit's second resonant frequency (fr_2) occurs at a higher frequency when C_S looks like a short-circuit and the reactances of L_s and C_P are equal and opposite. It is the parallel mode resonant frequency (fr_2) that is usually specified as a crystal's operating frequency.

The Hartley, Colpitts and Modified Colpitts crystal-controlled oscillators

Figure 4 below and Figures 5, 6, 7 and 8 on the next pages show examples of the Hartley, Colpitts and Modified Colpitts oscillators implemented using a crystal instead of the series inductor or series capacitor in the positive feedback network. The operation of these circuits is the identical to the LC oscillators discussed the previous chapter. Importantly, the frequency of oscillation is set by the crystal's parallel-mode resonant frequency (fr_2) and this is true of most cyrstal-controlled oscillators.

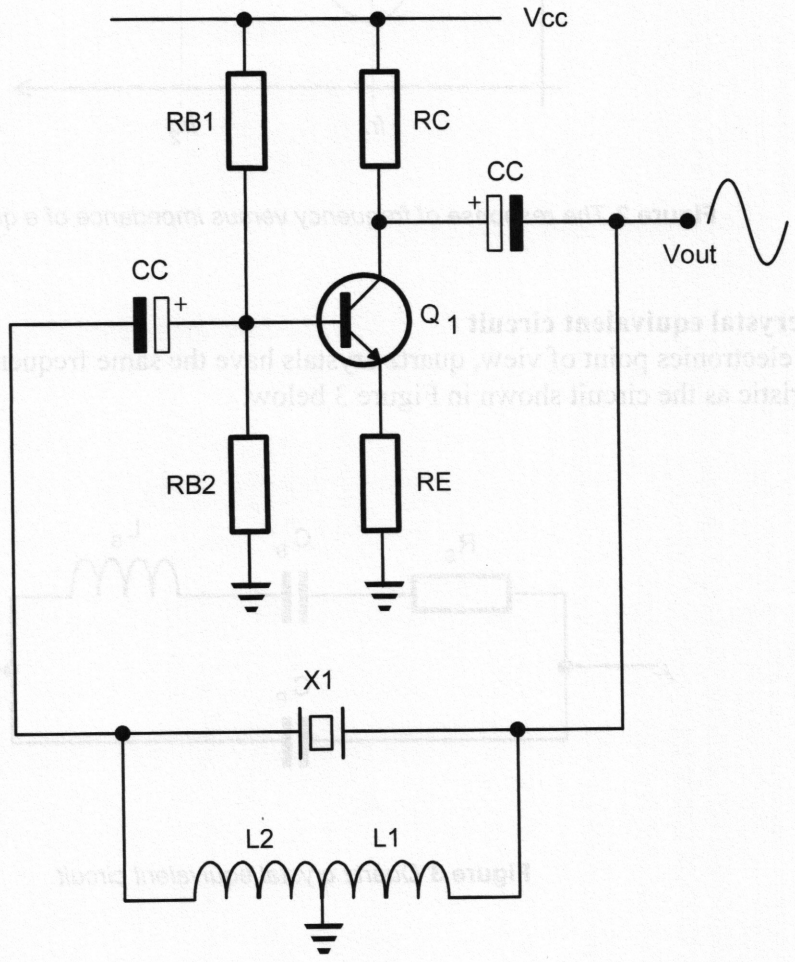

Figure 4 *Voltage divider biased, common emitter BJT crystal-controlled Hartley oscillator*

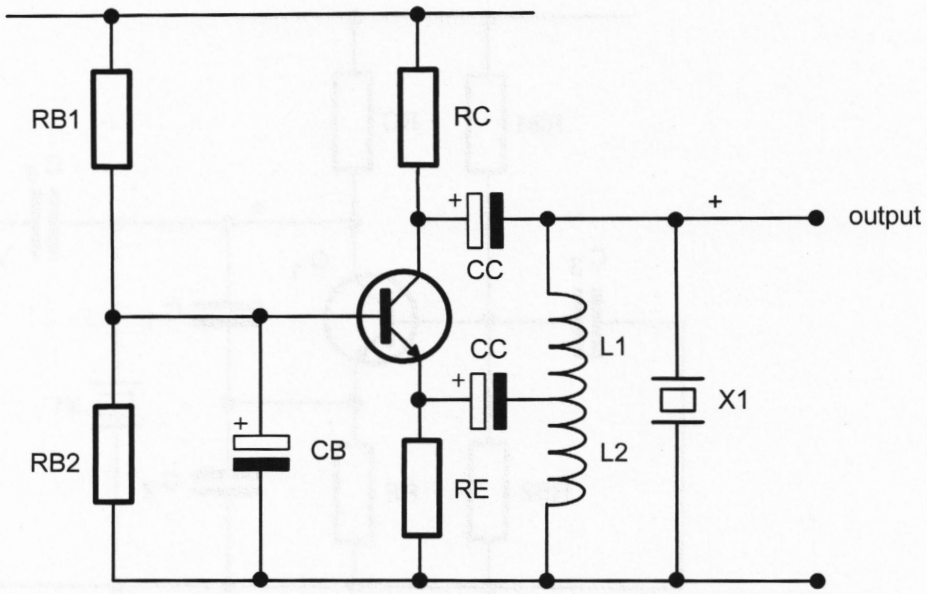

Figure 5 *Voltage divider biased, common base BJT crystal-controlled Hartley oscillator*

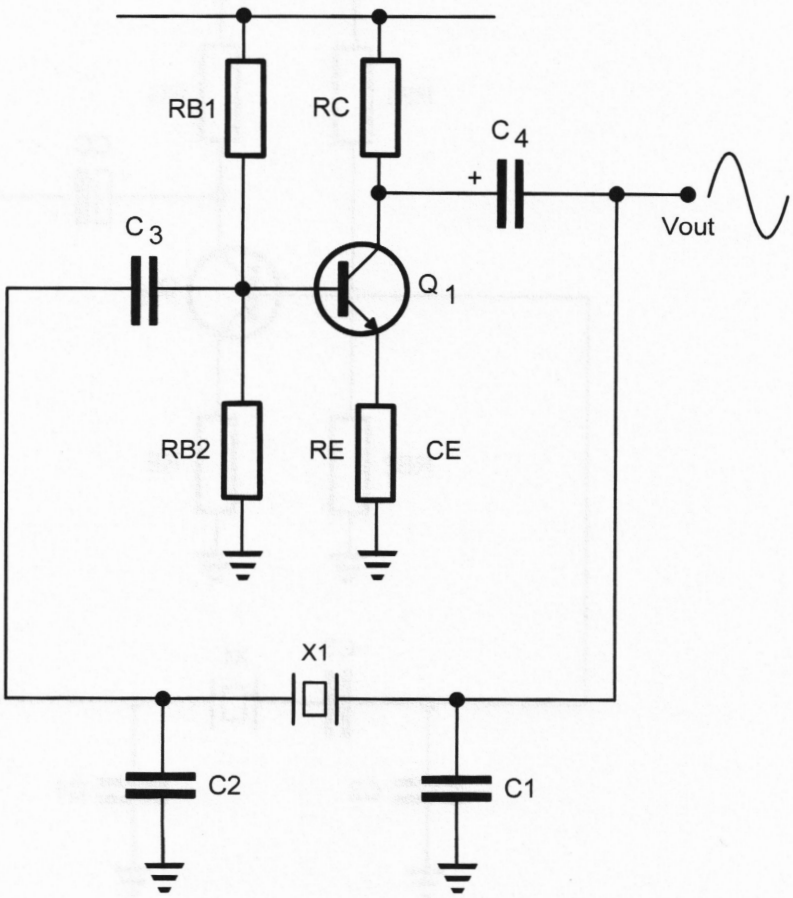

Figure 6 *Voltage divider biased, common emitter BJT crystal-controlled Colpitts oscillator*

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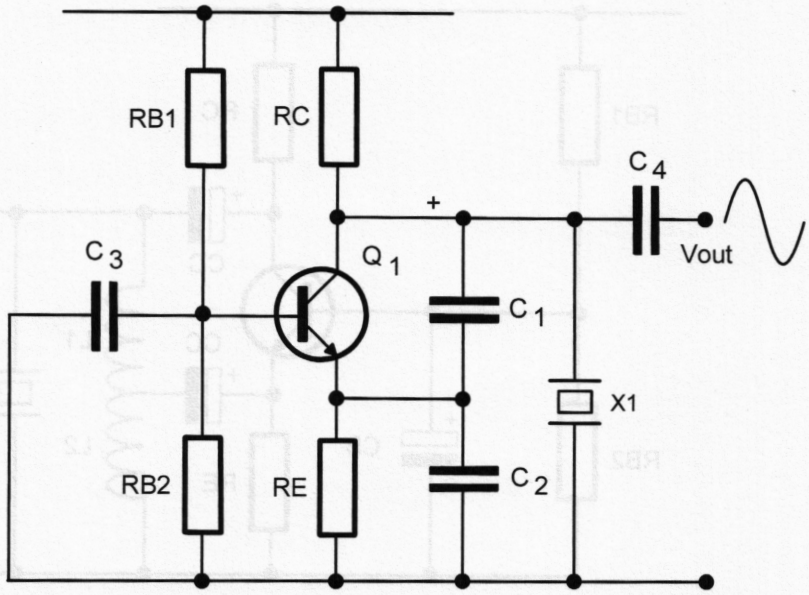

Figure 7 *Voltage divider biased, common base BJT crystal-controlled Colpitts oscillator*

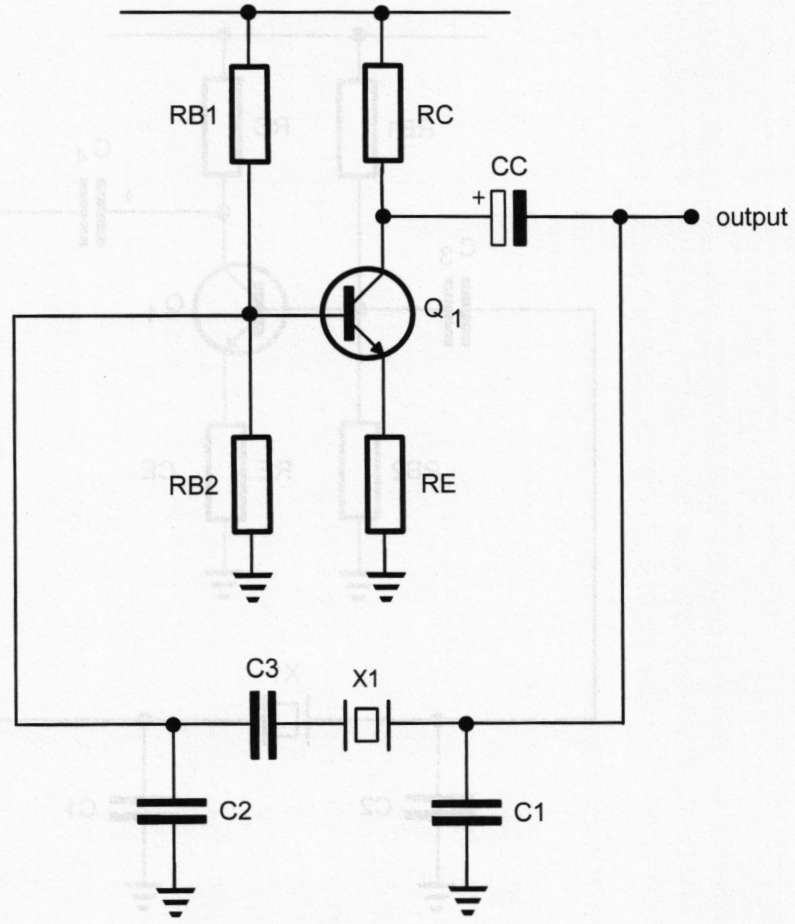

Figure 8 *Voltage divider biased, common emitter BJT crystal-controlled Modified Colpitts oscillator*

Note 1: The Modified Colpitts oscillator in Figure 8 would oscillate at a frequency that is close to the crystal's fr_2 but not exactly at that frequency given the inclusion of *C3*. This may seem like an odd thing to do but *C3* could be made variable expressly for the purpose of tweaking the circuit's frequency of oscillation.

Note 2: The values of the capacitors in the positive feedback path of the Colpitts and Modified Colpitts oscillators have to be chosen (a design issue) to facilitate oscillation at the crystal's specified operating frequency. They can't simply be random values otherwise they risk either not allowing the oscillator to start-up, or changing the circuit's frequency of oscillation.

Testing crystals

Suppose that you suspect that the crystal is faulty, how do you test it? Figure 10 below shows an arrangement for doing so.

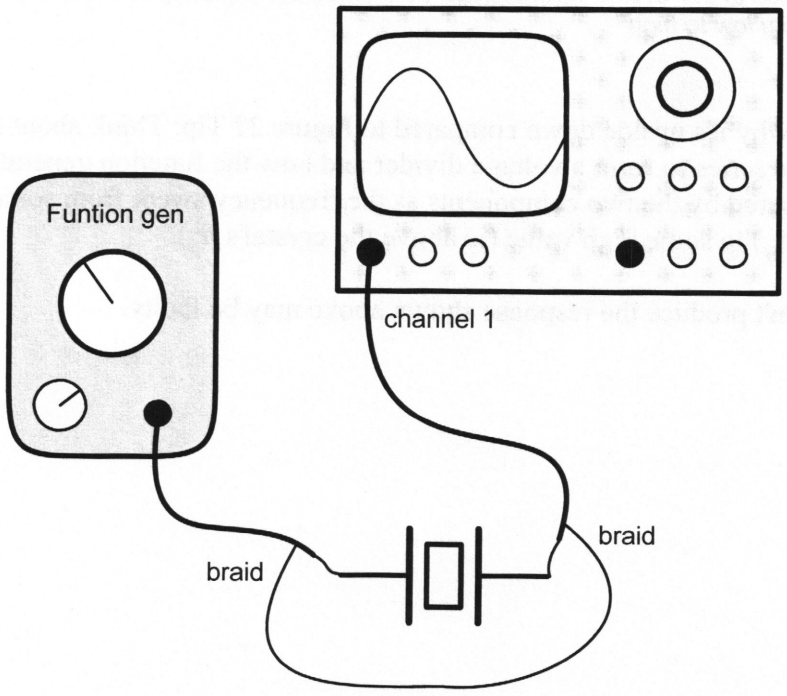

Figure 10 *The arrangement for testing a crystal*

As you can see, the crystal is placed in series with the function generator (adjusted to output a sinewave) and the CRO. Because the crystal is in series with the CRO's input resistance, it sets up a voltage divider and so the CRO measures an input voltage that is smaller than the function generator's output voltage (with the difference dropped across the crystal). Importantly, given the crystal's frequency response (see Figure 2), as the function generator's output is swept over a range of frequencies the CRO measures a changing potential difference. Specifically, as the function generator's output is swept from a low frequency to a high frequency, the response of the CRO's measured input voltage looks like Figure 11 on the next page.

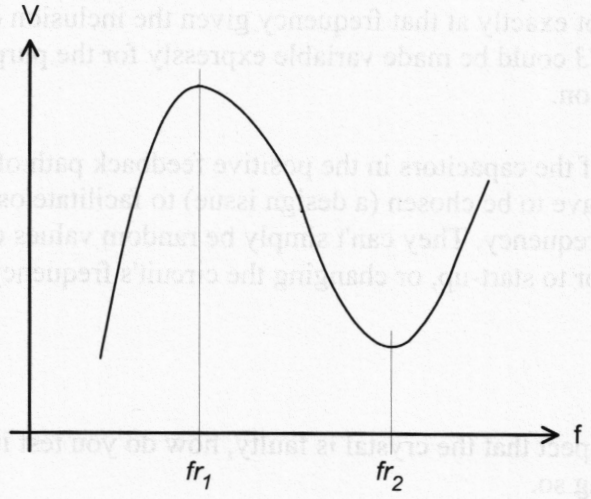

Figure 11 *The response of the CRO's input voltage as the output frequency of the function generator in Figure 10 is varied from low to high*

(Can you work out why it's upside down compared to Figure 2? Tip: Think about a crystal and a resistor connected in series to form a voltage divider and how the function generator's output voltage would be shared by the two components as the frequency swept from some low value (ie below the crystal's fr_1) to some high value (ie above the crystal's fr_2).

A crystal that couldn't produce the response shown above may be faulty.

Fault-finding BJT amplifier Hartley, Colpitts and Modified Colpitts oscillators

Before discussing specific fault-finding techniques for the Hartley and Colpitts oscillators discussed in this chapter, it's important to again briefly revisit the questions you should ask yourself when you start:

- Is the loop still closed?

  It can be useful to perform a visual inspection of the circuit to identify any possible poor solder joints or physical damage to components or the circuit board.

- Is the oscillator actually faulty?

  To minimise the risk of the CRO loading the circuit and stopping it from oscillating, use an attenuated CRO probe.

- Is the power supply working and does it connect to every component that it should?

  The first voltage measurements you need to take should be tests of the amplifier's power supply connections.

- Is the oscillator being loaded?

  If you can't find the fault in the oscillator circuit, keep in mind that a fault elsewhere in the system may be loading it and preventing it from starting up.

Problems with the oscillator oscillating at the wrong frequency

For Hartley, Colpitts and Modified Colpitts oscillators implemented using an LC combination in the positive feedback network, you should expect there to be a difference between the oscillator's theoretical and measured output frequencies. However, for well designed circuits, the difference shouldn't exceed the tolerance of the components that set the frequency of oscillation (that is, the inductor(s) and capacitor(s) in the positive feedback network).

For the crystal-controlled Hartley and Colpitts oscillators, you should expect the difference between the oscillator's theoretical and measured output frequencies to be extremely small (about 1Hz of error, or less, for every one million Hertz). If the error is larger than this, and you trust your instrumentation, then the components in the positive feedback network need checking.

For the crystal-controlled Modified Colpitts oscillator, the crystal sets the approximate frequency of oscillation but the capacitor in series with it changes that frequency by a small amount. Given capacitors have tolerance then you would expect there to be a small difference between the theoretical and measured output frequencies.

Problems with a clipped output signal

If the oscillator's output consists of distortion when it shouldn't, or more distortion than usual, it's an indication that the circuit's biasing has changed by some amount and is no-longer optimised to the circuit's operation. This means that the BJT's biasing resistors need checking (recall that these are the resistors that set-up the BJT circuit's quiescent DC voltages). And, if an RFC is being used in the BJT's collector arm its DC resistance should be compared to a known functional instance of the same type of inductor having the same value.

Problems with the oscillator not oscillating

If the circuit is not oscillating at all, the problem is unlikely to be one of the components in the positive feedback network. That's because one of these components will have had to change value substantially, or have completely failed altogether, for the circuit to stop oscillating. But this is unlikely given they don't work very hard electrically. Exceptions to this generalisation include; if the equipment is fairly old (in which case one of these components may have simply failed due to age), or if the equipment has been dropped and one of the component leads has sheared through (but this should have been identified earlier when performing a visual inspection of the circuit).

Given the simplicity of the BJT amplifier used to implement the Hartley, Colpitts and Modified Colpitts oscillator designs in this workbook, the simplest fault-finding solution would be to remove the BJT and check it using your DMM's diode test function. You'd start with the BJT because it's the most likely component in the circuit to fail. But, if it's ok, the problem is likely one of its biasing resistors, or the RF choke in the collector arm if one is used, which you could remove one at a time to check.

The fault-finding approach can be a little more sophisticated than this and would be more efficient for circuits implemented using SMD components (because of the difficulty in de-soldering and re-soldering them) or for more sophisticated designs version of these circuits. Moreover, you have been taught how to fault-find BJT amplifier circuits for an earlier unit so you know how to go about this.

To appreciate that last point, it's important to understand that when the circuit isn't oscillating, there must only be DC voltages present in the amplifier circuit. And, as the positive feedback network is connected to the amplifier's input and output using coupling capacitors, the network can be ignored because capacitors block DC. What's left of the circuit to check is shown in Figure 12 below and a DC voltmeter must be used because there are no AC signals present.

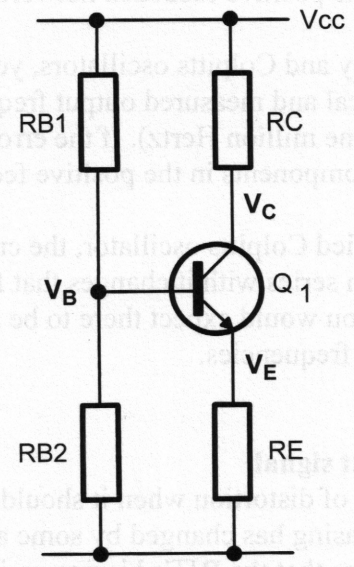

Figure 12 *A voltage divider biased BJT*

So, let's put your fault-finding skills to the test. Figure 13 below shows the circuit in Figure 12 but with values for the key quiescent voltages in the circuit (rounded to one decimal place).

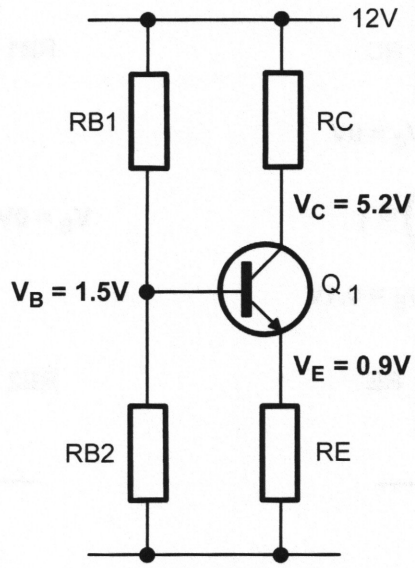

Figure 13

For Figures 14 to 23, the circuit is the same as the one above but one or more of the voltages have changed in response to a component fault. For each circuit, identify which component is faulty and what's wrong with it.

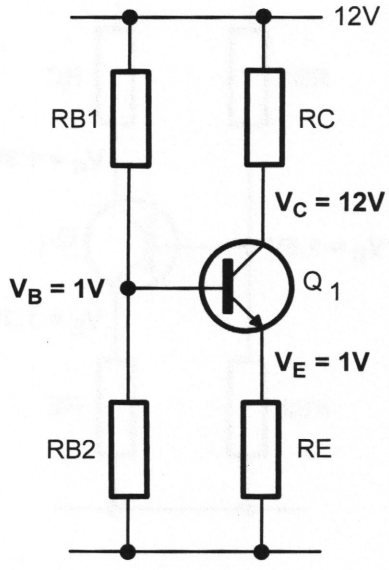

Figure 14

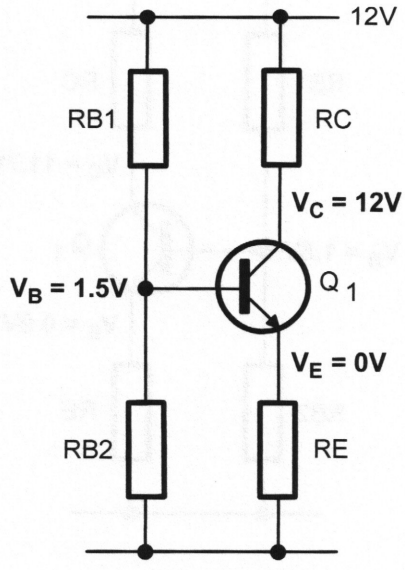

Figure 15

Base-emitter short

Base emitter open circuit

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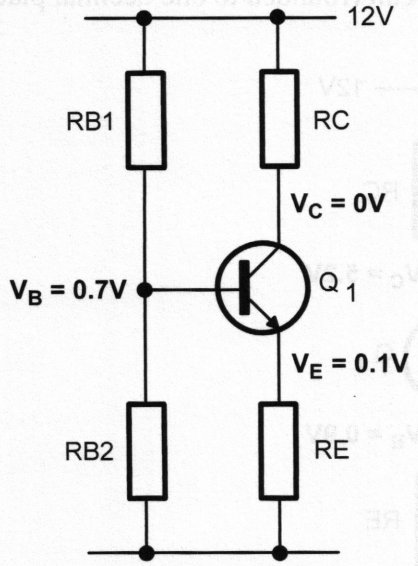

Figure 16

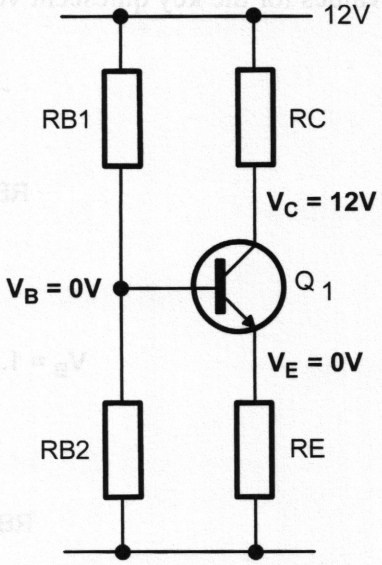

Figure 17

RB1 - open circuit

RB2 - open circuit

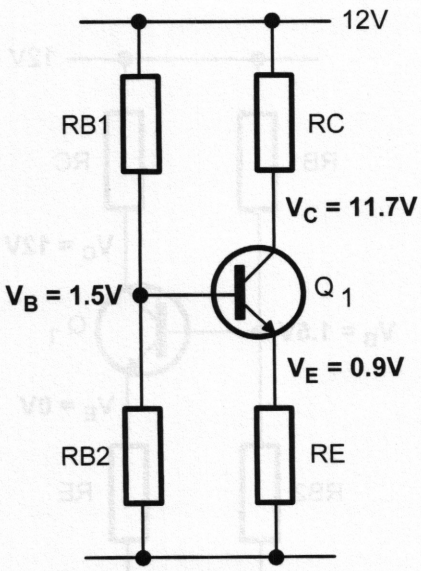

Figure 18

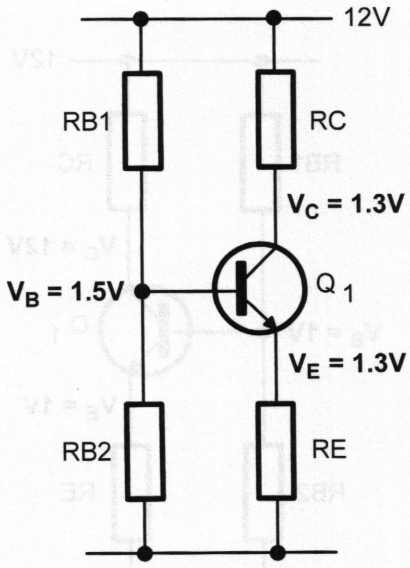

Figure 19

collector path open

BJT collector emitter short

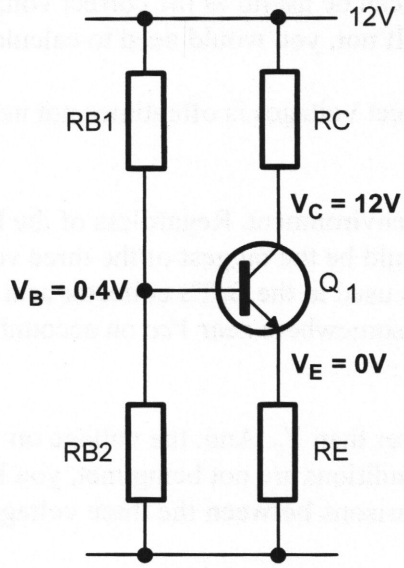

Figure 20

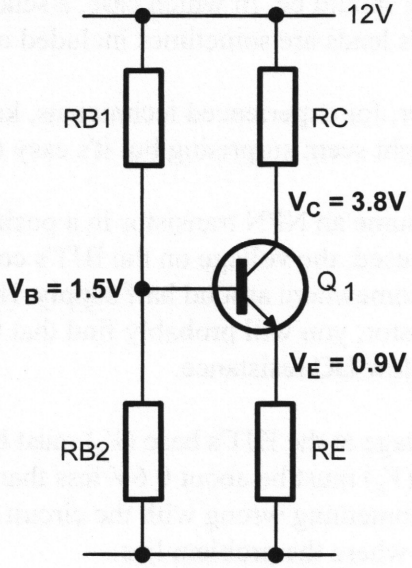

Figure 21

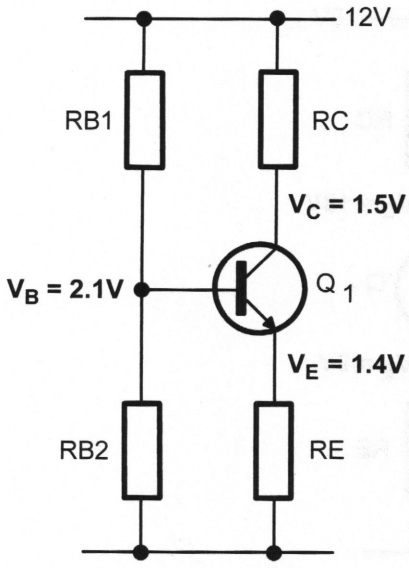

Figure 22

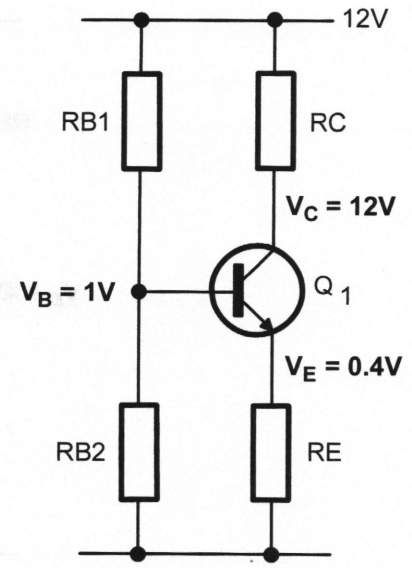

Figure 23

Open circuit

Collector at transistor

It's useful to be able to compare the faulty circuit's measured values of V_C, V_B and V_E to the values that they should be. In which case, a schematic diagram can be useful as the correct voltages on the BJT's leads are sometimes included on the drawing. If not, you would need to calculate them.

However, for experienced technicians, knowing the correct voltages is oftentimes not necessary. That might seem surprising but it's easy to explain.

Let's assume an NPN transistor in a positive supply rail environment. Regardless of the biasing method used, the voltage on the BJT's collector (V_C) should be the biggest of the three voltages and sit somewhere around half supply. If an RF choke is used in the BJT's collector arm instead of a resistor, you will probably find that the voltage sits somewhere near *Vcc* on account of the choke's low DC resistance.

The voltage at the BJT's base (V_B) must be a voltage lower than V_C. And. the voltage on the BJT's emitter (V_E) must be about 0.6V less than V_B. If these conditions are not being met, you know there's something wrong with the circuit and then comparisons **between** the three voltages can tell you where the problem lies.

To prove this point, consider the faulty circuit in Figure 24 below. It's a circuit whose correct voltages you don't know. Complicating the matter, it's a base bias circuit which is not a circuit that you'll be especially familiar with from your studies (we tend to focus on the voltage divider biasing method as it makes things a little easier for teachers to explain and for students to understand). But, you should be able to identify the circuit fault from the voltages given. Give it a go (assume the power supply voltage is correct).

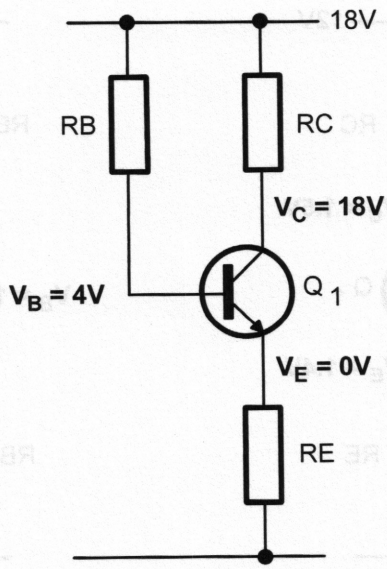

Figure 24 *What component is faulty in this circuit and what's wrong with it?*

Voltage-controlled oscillators

Voltage-controlled oscillators (VCOs) are circuits that output an AC signal at a frequency that has been predetermined by design but can be made to vary electronically by the application of an external DC or AC voltage on an input to the VCO.

The predetermined output frequency is typically called the "centre" or "rest" frequency.

The amplitude of the input voltage to a VCO is made to go up or down to cause the output to either: a) go up and down in frequency (making the relationship between the two proportional); or down and up in frequency (so the relationship is inversely proportional).

VCO applications

Applications for VCOs include (but are not limited to):

- Function generators (many of which have a VCO facility)
- The implementation of a very widely used circuit called the *phase-locked loop* (with one example being to demodulate FM radio signals)
- The generation of FM signals (with one example being the transmitter of an FM broadcast radio station)
- Musical instruments (like the electronic keyboard/piano)
- Analog telemetry ("telemetry" is the sending of measured information like temperature, air pressure, etc to another location electronically)

VCO output waveshape

VCOs can be designed to output any waveshape including sinewaves and rectangular waves. This chapter will only discuss the former with the latter discussed in the next chapter.

VCO voltage range

The *voltage range* of a VCO (also called the *tuning voltage range*) is the minimum and maximum allowable voltages that can be connected to the VCO's input.

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VCO sensitivity

The *sensitivity* of a VCO (also called the *tuning sensitivity*) is how much the output frequency changes for a change per unit of input voltage change. This figure is usually quoted in Hertz per volt (Hz/V) though smaller voltage references can be used (eg Hz/mV).

To give an example, suppose a VCO has a rest frequency of 100kHz and a sensitivity of 10kHz/V. Then, if the input is 0V, the VCO outputs a 100kHz signal.

But if the input is increases to 0.5V, the VCO's output frequency increases to 105kHz. And if the input continues to increase to 1V, the VCO's output increases to 110kHz and so on. If the polarity of the input reverses changing to -1V, the output voltage decreases to 90kHz.

(Importantly, the changes in output frequency are continuous rather than stepped, though the latter would be relatively easy to implement if that was needed.)

VCO linearity

The *linearity* of a VCO is a measure of how consistent the sensitivity figure is over a range of input voltages.

To explain this using numbers, suppose our 100kHz VCO with a sensitivity of 10kHz/V described on the previous page was perfectly linear. This would mean that every 1V change of input would produce the same change in output frequency. Putting this another way, a 1V input would give 110kHz out, a 2V input would give 120kHz out, a 3V input would give 130kHz out and so on.

But if the same VCO was not perfectly linear, every 1V change of input would produce a slightly different amount of change in output frequency. So, a 1V input might give 110kHz out, a 2V input would give 119kHz out, a 3V input would give 127kHz out and so on.

As you can see from this example, the size of the change in output frequency is getting smaller for each additional volt of change on the input. The first volt of change on the input changed the output frequency by 10kHz, the second changed the frequency by 9kHz, and the third changed the frequency by 8kHz. (Note: The figures quoted here are exaggerated for ease of writing and reading. The linearity of VCOs would typically be better than this and involve smaller differences between the frequency changes for each unit of input voltage change.)

The concept of VCO linearity can also be described graphically. The graph on the left in Figure 25 below represents the performance of a perfectly linear VCO while the graph on the right represents the performance of a VCO with some non-linearity.

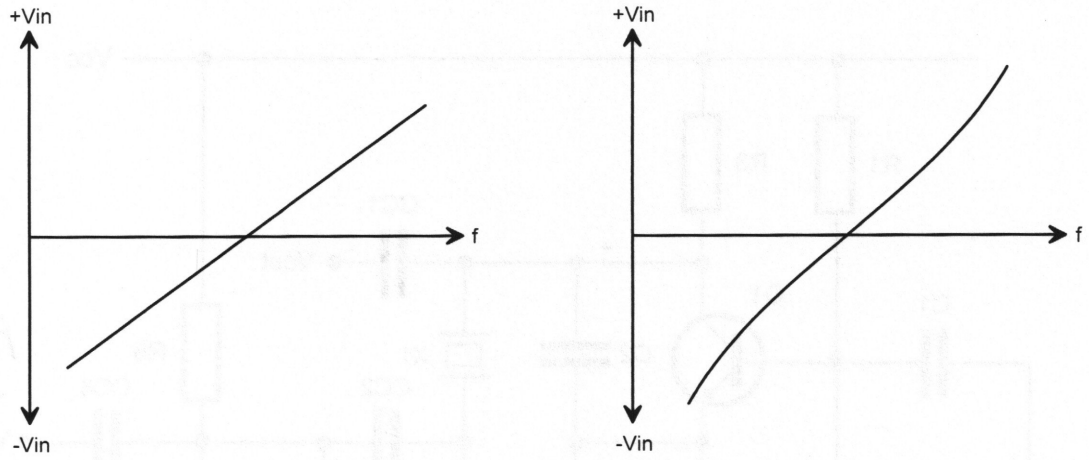

Figure 25 *Left) The performance of a linear VCO; Right) The performance of a VCO with some non-linearity*

Does the linearity matter? It depends on the application. For analog telemetry, you would likely need a high degree of linearity to reduce any error in the translation of changes in the measured values into changes in frequency. Otherwise, the errors in translation would undermine the accuracy of the measurements in the first instance. (With that said, digital systems would dominate the telemetry space these days as one of their advantages is that they avoid this very problem.)

For the FM modulaton/demodulaton in broadcast radio you would need a respectable degree of linearity for good sound quality. But for the FM modulation/demodulaton in an FM two-way radio system, the linearity wouldn't need to be as good because the sound quality in two-way radio speech communications doesn't need to be as good as for radio.

VCO circuit example

VCOs are implemented as either discrete component circuits (using all manner of circuit designs) or, more likely these days, using dedicated VCO ICs of which there are many. An example of a discrete component sinusoidal VCO circuit is shown in Figure 26 below.

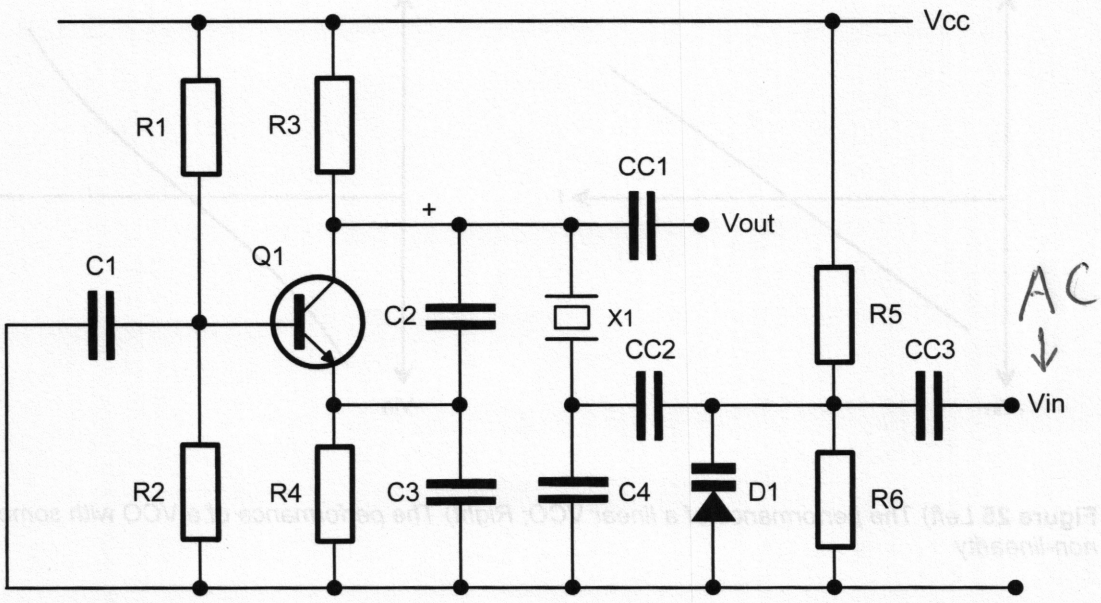

Figure 26 *Sinusoidal VCO based on the crystal-controlled Modified Colpitts oscillator*

At first glance, this looks like a busy little circuit. However, a more careful look shows that its actually the crystal-controlled Modified Colpitts oscillator that you've already learnt about, adapted to operate as a VCO (This particular circuit has been taken from the schematic diagram of an FM two-way radio.). Its operation is explained over the next few pages.

First, Figure 27 below shows a voltage divider biased, common base Modified Colpitts (or Clapp) oscillator. It's shown here to help you identify this portion of the VCO in Figure 26. Take a moment to compare the two drawings.

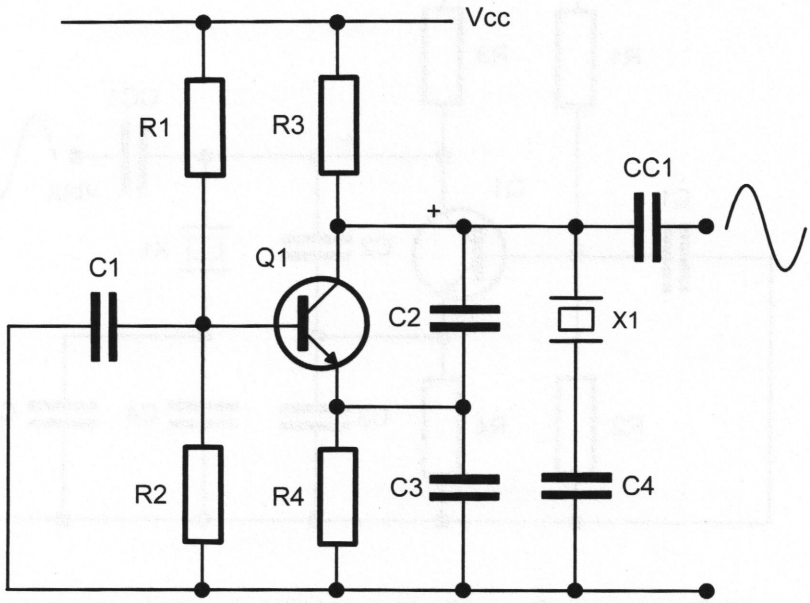

Figure 27 *A voltage divider biased, common base Modified Colpitts oscillator which is the basis of the VCO in Figure 26*

An important thing to know about this circuit is that the inclusion of *C4* to change this circuit from the Colpitts oscillator to the Modified Colpitts oscillator changes the circuit's frequency of operation a little so that it's no-longer at the crystal's specified frequency. This seems like an odd thing to do given the benefits of using a crystal to set the frequency but keep reading.

Now, suppose a capacitor was connected across *C4* as shown in Figure 28 below.

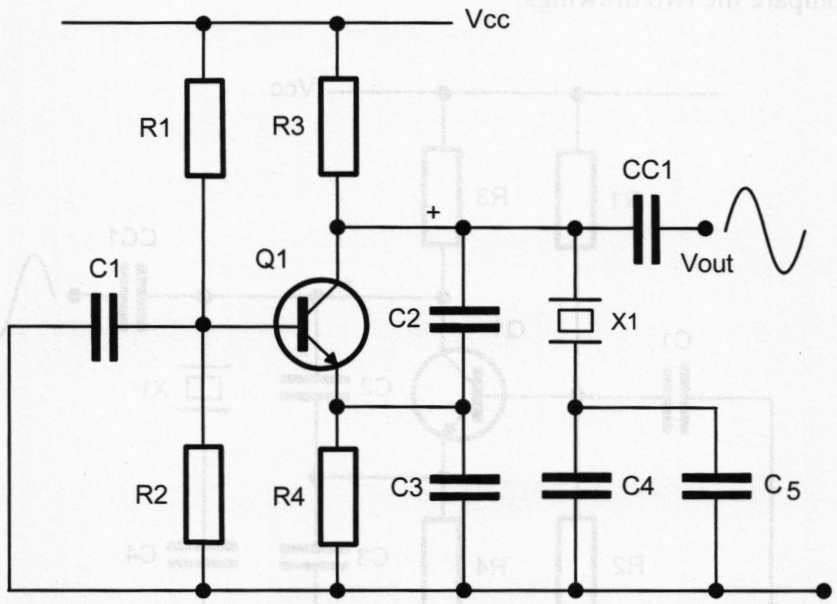

Figure 28 *The circuit in Figure 27 with an additional capacitor connected across C4*

As *C4* and *C5* are in parallel, the total capacitance between the crystal and common is the sum of the two. As such, both capacitors influence the circuit's frequency of oscillation.

Now suppose *C5* was a variable capacitor as shown in Figure 29 below.

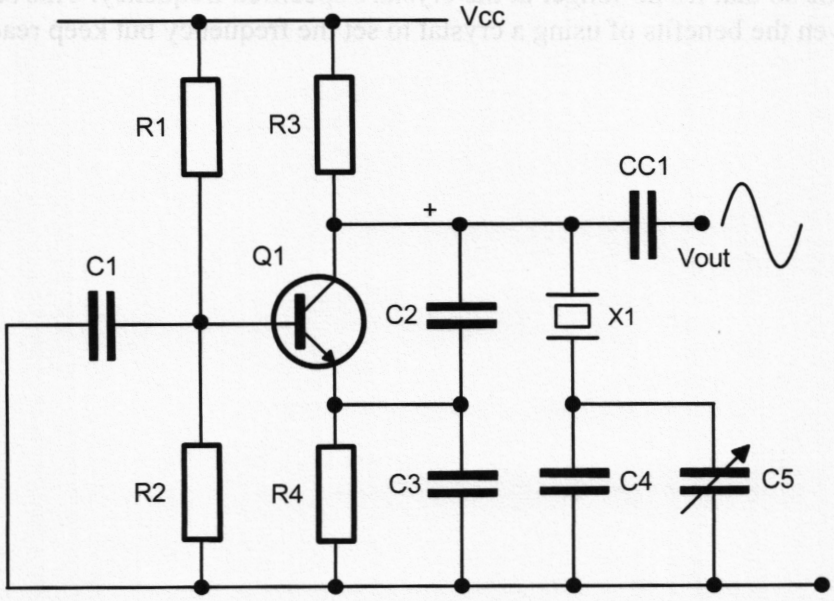

Figure 29 *The circuit in Figure 28 with C5 made variable*

As *C5* is variable, this must mean that the total capacitance between the crystal and common is now variable. As such, the circuit's frequency of oscillation is variable.

And this brings us to a component that you have likely not been taught about before in your studies; the *varicap diode* (also known as a *varactor diode*). The schematic symbol of the varicap diode is shown in Figure 30 below.

Figure 30 *The schematic symbol of a varicap diode*

To understand the operation of the varicap diode you need to go back to p-n junction operation. Recall that when n-type and p-type semiconductor materials are brought together to create a p-n junction, a depletion layer of current carriers is formed on both sides of the junction. Being depleted of current carriers, the depletion layer is a region of high resistance relative to the resistance of n-type and p-type materials and so a small value capacitor is formed. The two semiconductor materials act as the capacitor's plates and the depletion layer acts as the capacitor's dielectric.

Now, you're used to thinking about the operation of diodes when they're forward biased but here you need to recall what happens when the they're reverse-biased. The greater the reverse bias, the thicker the depletion layer becomes. So, if you think of the reverse-biased p-n junction as a capacitor then, as the depletion layer gets thicker, the plates effectively move further apart. And, if you recall the factors that affect capacitance, the further apart a capacitor's plates, the smaller the capacitance. Obviously, the reverse must also be true.

All reverse biased diodes have some inherent capacitance that behaves this way. But varicap diodes are designed to optimise this effect and cause as much variation as possible when reverse-biasing the device across its allowable range. This turns the diode into a variable capacitor whose value is controlled by the voltage across it.

This brings us back to the VCO in Figure 26 which is shown again in Figure 31 below for your convenience.

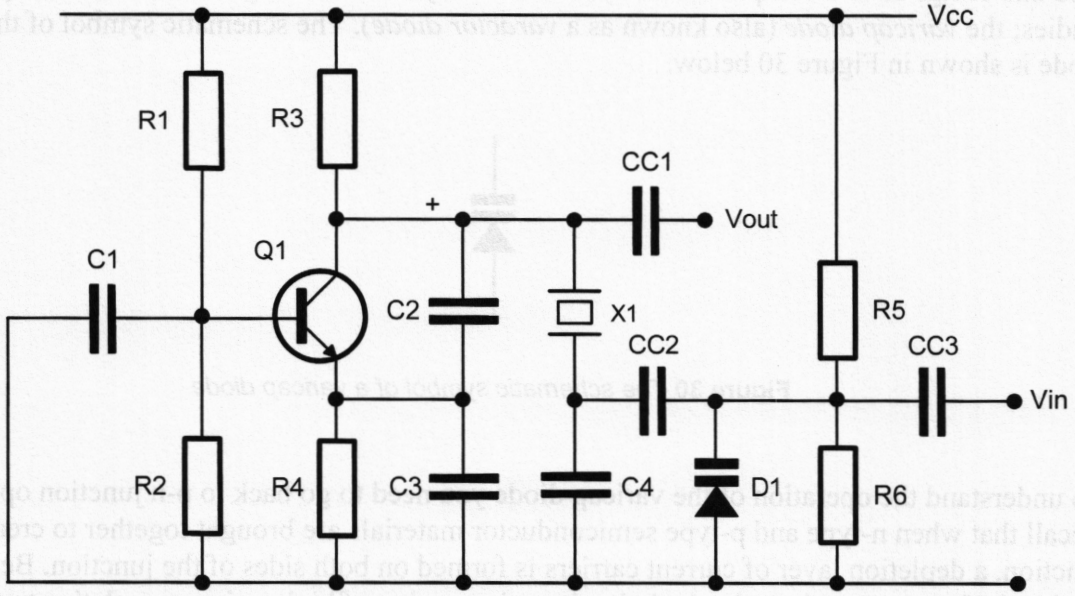

Figure 31 *The sinusoidal VCO based on the crystal-controlled Modified Colpitts oscillator in Figure 26*

The varicap diode (*D1*) is connected across *C4* to set the total resistance between the crystal and common. Together, these two components set the circuit's frequency of oscillation to a value in the region of the crystal's specified frequency of operation.

Resistors *R5* and *R6* develop a reverse bias voltage across *D1* (to a ballpark figure of a few volts), setting the varicap diode's capacitance to a figure somewhere between the limits of its variable range.

The coupling capacitor *CC3* is used to couple an AC input voltage across the varicap diode. As the AC input voltage varies, it varies the reverse bias across *D1* varying its capacitance. This varies the total capacitance between the crystal and common which in turn varies the circuit's frequency of oscillation.

Skill practice 4

Verifying the operation of an integrated circuit VCO implemented using a DMM and an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you'll be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Emona ETT-101 "Biskit" Telecommunications Trainer
- DMM

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
■ Trip hazards (eg students bags) ■ Objects dropped on feet (while equipment is taken to and from workbenches). Others: _____ _____ _____	■ Move bags and other objects from walkways ■ Plan lifting of equipment Other: _____ _____ _____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Read the notes below before continuing.

About the Biskit
The ETT-101 is an Australian made training aid for students studying electronics, particularly electronic communications. If you inspect the unit's faceplate, you'll notice that it's broken into discrete modules with names like *Buffer*, *Tuneable LPF*, etc that you'll recognise from your previous studies. Relevant to this chapter, there's a sinusoidal and digital VCO module (bottom row, second from left). You'll be using it for this exercise.

The VCO's *SINE* output is a 4Vpp sinewave and the *DIGITAL* output is a 5Vpp squarewave with a DC offset to set the signal's peaks to ideal TTL logic levels. The *SINE* and *DIGITAL* outputs are identical frequencies. The VCO's voltage range is -3V to +3V.

Finally, you'll notice that the VCO has several controls and these are explained below:

Range: This is the two-position slider switch. As its name implies, it lets you manually select one of two sets of output frequency ranges. The *LO* position outputs frequencies between 1kHz & 17kHz and the *HI* position outputs between 60kHz & 140kHz.

Freq: This is the *Frequency Adjust* control which lets you set the VCO's output to a frequency within the *LO* and *HI* range of frequencies.

Gain: This control sets the VCO's sensitivity (that is, how much the output frequency changes for each volt on its input).

4. Power up the trainer.

5. Locate the VCO and set its range control to *HI*.

6. Set the VCO's *Freq* control to about the middle of its travel.

   Note: There's no need to be exact in this adjustment because you'll accurately set the output frequency shortly.

7. Turn the VCO's *Gain* control fully clockwise.

8. Connect the CRO's Channel 1 input to the VCO's *SINE* output.

   Note: Ensure that the CRO lead's black plug is inserted into one of the several ground (GND) sockets on the trainer's faceplate. There are two in the middle between the upper and lower sets of modules.

9. Make the necessary adjustments to the CRO to display the VCO's output.

10. Connect the CRO's Channel 1 input to the VCO's *DIGITAL* output to confirm that there is a signal then return it to the *SINE* output.

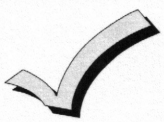
11. Activate the bench-mounted Function Generator's *EXT* frequency count mode.

12. Select the Function Generator's *100kHz* range.

    Note: This will set the Function Generator's frequency counter to the best range for measuring the frequency of signals around 100kHz. Recall that the best range for making measurements is usually the one with the highest resolution.

13. Connect the Function Generator's *EXT* input to either one of the VCO's outputs (it doesn't matter which one you use because the signals are the same frequency).

14. Vary the VCO's *Freq* control and verify that the VCO's output ranges from about 60kHz to about 140kHz.



The teacher needs to check your work at this point...

15. Set the VCO's output to as close to 100kHz as you can obtain.

16. Locate the Variable DCV module.

    Note: This should be the module to the left of the VCO. It's a source of DC voltage and you'll be using it to test the operation of the VCO.

17. Connect the DMM between the DC source's *VDC* and *GND* sockets.

18. Vary the DC source's *VDC* knob from fully clockwise to fully anti-clockwise while taking note of its output voltage.

    Note: You should find that the output voltage varies between -2.5V DC and +2.5VDC.

19. Set the Variable DCV module's output to about +0.5V.

20. Locate the Buffer module and set its *Gain* control to about the middle of its travel.

21. Connect the Variable DCV module's *VDC* output to the Buffer module's input.

    Note: The Buffer is an inverting amplifier with a variable gain from 0 to about -10V. You're using it here to amplify the Variable DCV module's output voltage.

22. Connect the DMM between the Buffer's output and *GND* sockets.

23. Vary the Buffer's *Gain* control from fully clockwise to fully anti-clockwise while taking note of its output voltage.

    Note: You should find that the output voltage varies between 0V DC and about -5VDC.

24. Turn the Buffer's *Gain* control fully anti-clockwise.

25. Connect the Buffer's output to the VCO's input.

    Note: The VCO's output frequency should not change much, if at all.

26. Measure the VCO's output frequency and record this in the appropriate cell in Table 1 on the next page.

27. Set the VCO's input (by adjusting the Buffer's *Gain* control) to as close to -1V as you can obtain.

28. Measure and record the VCO's new output frequency.

29. Calculate and record the change in output frequency for the change from 0V.

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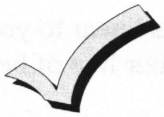
30. Set the VCO's input (using the Buffer's *Gain* control) to as close to -2V as you can obtain.
31. Measure and record the VCO's new output frequency.
32. Calculate and record the change in output frequency for the change from -1V.
33. Set the VCO's input (using the Buffer's *Gain* control) to as close to -3V as you can obtain.
34. Measure and record the VCO's new output frequency.
35. Calculate and record the change in output frequency for the change from -2V.
36. Set the VCO's input (using the Buffer's *Gain* control) to as close to -4V as you can obtain.
37. Measure and record the VCO's new output frequency.
38. Calculate and record the change in output frequency for the change from -4V.
39. Set the Variable DCV module's output to about -0.5V.
40. Repeat Steps 27 to 38 but this time for positive values of all voltages.

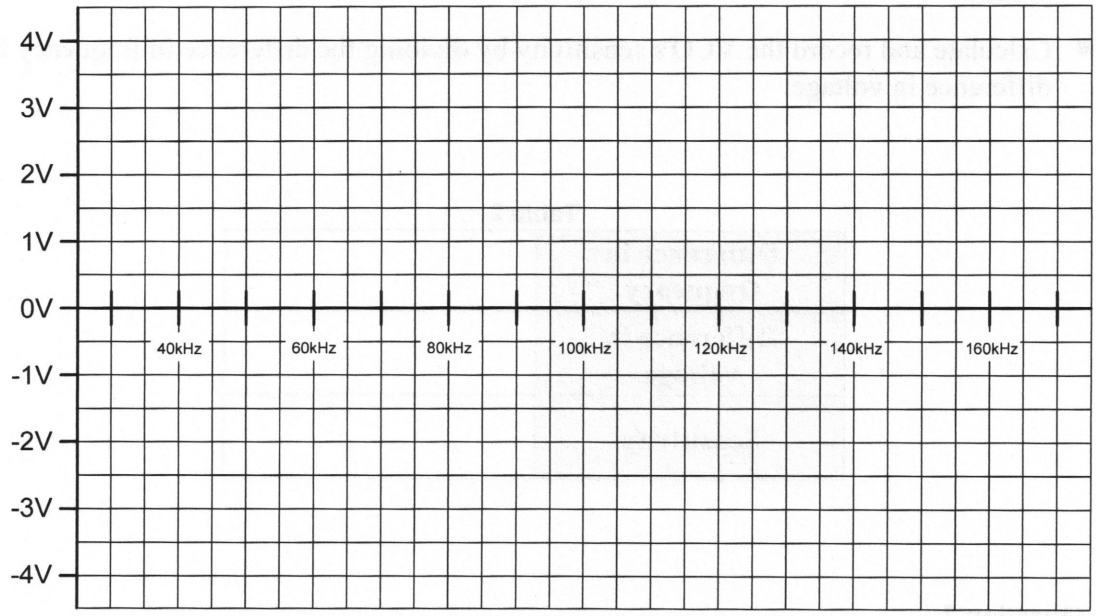
Table 1

DC voltage on the VCO's input	Output frequency	Change in output frequency
-4V		
-3V		
-2V		
-1V		
0V		
+1V		
+2V		
+3V		
+4V		



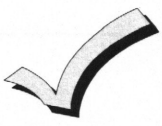
The teacher needs to check your work at this point...

41. Graph the results of your table below.



Question 1

Just from a simple visual inspection, does this VCO's response seem linear to you? Explain your answer.



The teacher needs to check your work at this point...

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42. To determine the VCO's sensitivity figure in Hertz per Volt, perform the following steps:

- Identify the longest portion of the line that looks linear to you and, using a different coloured pen, mark the ends of this region on your line of best fit.
- Identify the closest data point at each end of the linear region that falls inside the linear region.
- Calculate the absolute difference between the two frequencies at these data points and record this figure in Table 2 below.
- Calculate and record the absolute difference between the two voltages for these data points.
- Calculate and record the VCO's sensitivity by dividing the difference in frequency by the difference in voltage.

Table 2

Difference in frequency	
Difference in voltage	
Sensitivity	

Question 2
Why can't you simply use one of the changes in voltage figures in Table 1 as the VCO's sensitivity figure?

Question 3
Calculate the average of the change in frequencies in Table 1 and compare this to the sensitivity figure in Table 2? Are they close?

Question 4

Explain why using the graphical method of determining the VCO's sensitivity would be more reliable than the averaging method. Put another way, what mistake could you make if you were using the averaging method?

The teacher needs to check your work at this point...

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Student notes

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

Questions 1 to 3 refer to the circuit in Figure 1 below

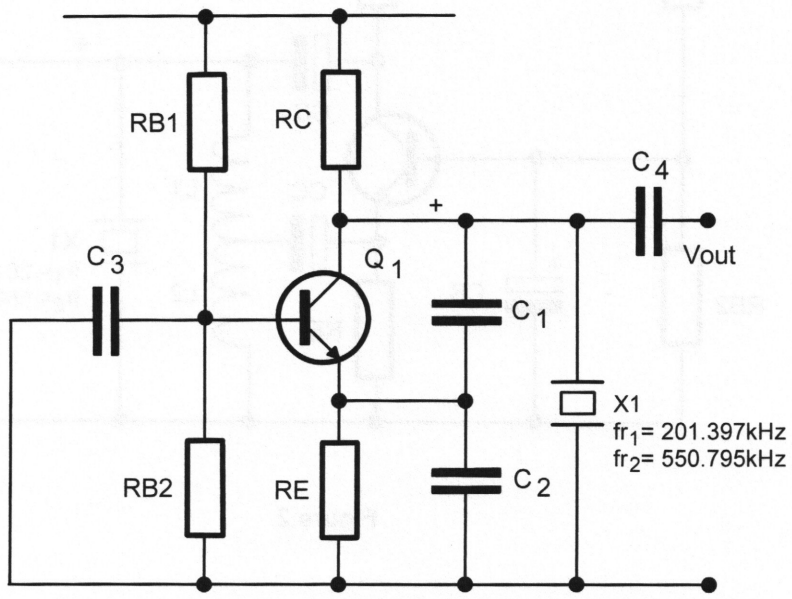

Figure 1

1. What's the name of the oscillator?

   ☐ Crystal-controlled Modified Colpitts oscillator
   ☐ Crystal-controlled Colpitts oscillator
   ☐ Crystal-controlled Hartley oscillator
   ☐ Series-mode crystal-controlled oscillator

2. What is the shape of the oscillator's output signal?

   _____

3. What is the oscillator's frequency of oscillation?

   _____

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Questions 4 to 6 refer to the circuit in Figure 2 below

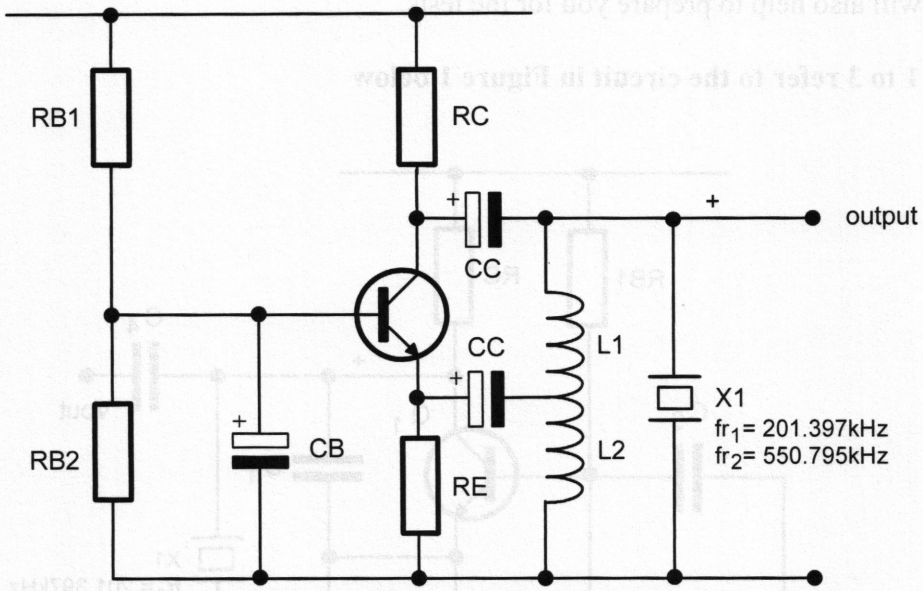

Figure 2

4. What's the name of the oscillator?

- ☐ Crystal-controlled Modified Colpitts oscillator
- ☐ Crystal-controlled Colpitts oscillator
- ☐ Crystal-controlled Hartley oscillator
- ☐ Series-mode crystal-controlled oscillator

5. What is the shape of the oscillator's output signal?

_____

6. What is the oscillator's frequency of oscillation?

_____

7. What do the initials VCO represent with regard to oscillator circuits?

- ☐ Variable-controlled oscillator
- ☐ Varactor-controlled oscillator
- ☐ Vertically-controlled oscillator
- ☐ Voltage-controlled oscillator

8. Give two applications for a VCO.

_____

_____

_____

9. What oscillator circuit is the VCO in Figure 3 below based on?

_____

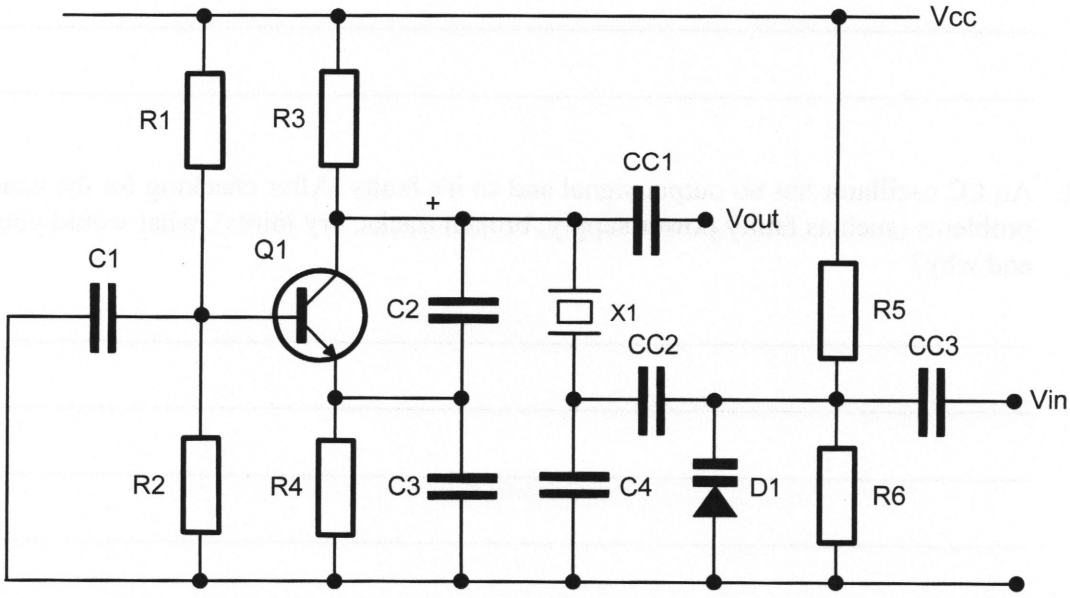

Figure 3

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10. What are two names for the component in the circuit marked *D1*?

11. Briefly explain how the physical construction of a capacitor (ie two plates and a dielectric) is implemented by the p-n junction of a diode.

12. Briefly explain how the p-n junction's inherent capacitance can vary.

13. An LC oscillator has no output signal and so it's faulty. After checking for the usual problems (such as faulty power supply, broken tracks, dry joints), what would you do next and why?

14. What piece of test equipment can be used to test inductors and capacitors to see whether they are ok and whether they're the correct value?

15. The circuit in Figure 4 is not oscillating. What component is faulty and what's wrong with it given the quiescent DC voltages shown in the circuit?

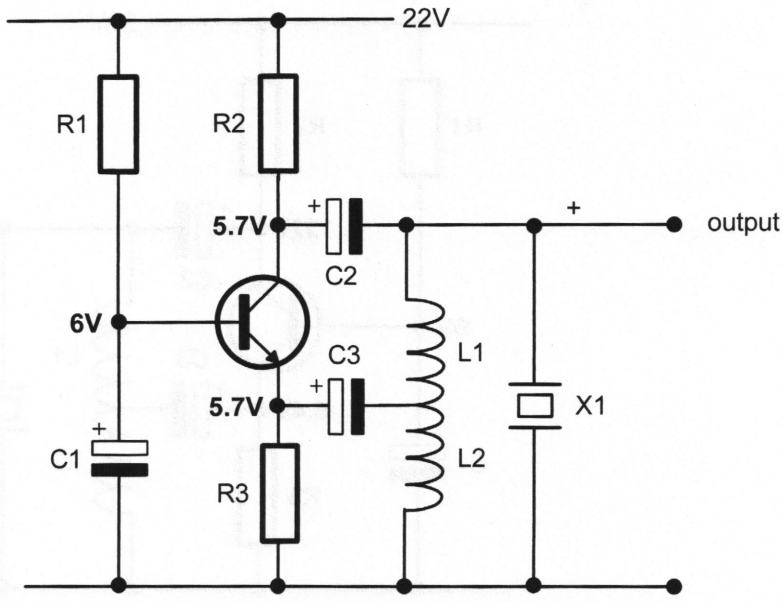

Figure 4

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16. The circuit in Figure 5 is not oscillating. What component is faulty and what's wrong with it given the quiescent DC voltages shown in the circuit?

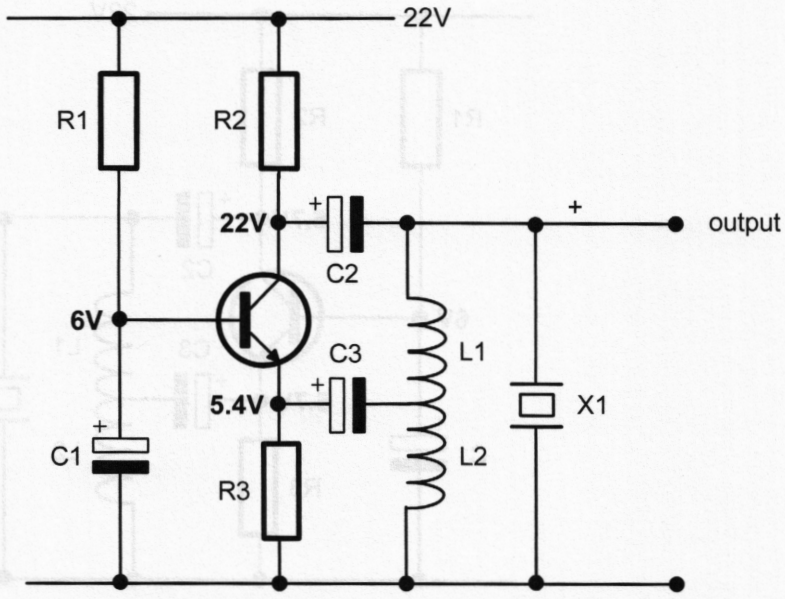

Figure 5

17. The circuit in Figure 6 is not oscillating. What component is faulty and what's wrong with it given the quiescent DC voltages shown in the circuit?

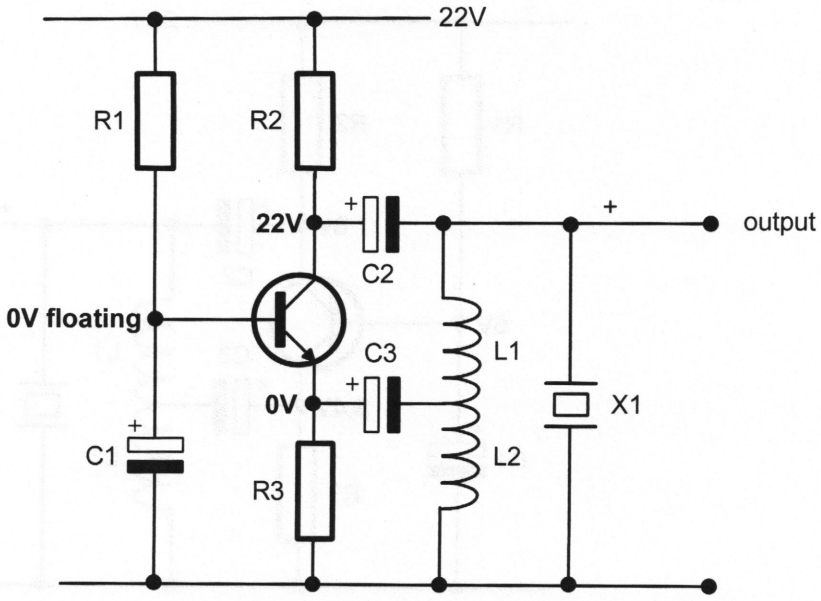

Figure 6

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18. The circuit in Figure 7 is not oscillating. What component is faulty and what's wrong with it given the quiescent DC voltages shown in the circuit?

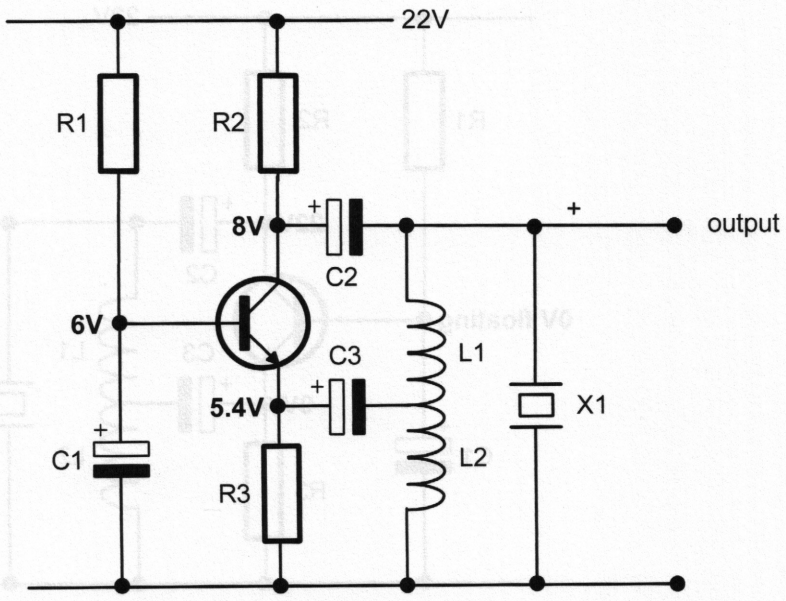

Figure 7

Section 5 Digital oscillators

Purpose To develop your ability to recognise and understand the operation of digital oscillator circuits.

Objectives At the end of this section you should be able to:

- Identify the Pearce oscillator in schematic diagrams
- Predict the output waveshape, frequency, amplitude, and absolute peak voltages of the crystal-controlled Pearce oscillator
- Explain the operation of the crystal-controlled Pearce oscillator in terms of Barkhausen's Criteria including why the output is not a sinewave
- Identify the RC relaxation oscillator implemented using a NOT gate with hysteresis in schematic diagrams
- Explain the basic principle of operation of RC relaxation oscillators using the circuit the NOT gate with hysteresis circuit
- Explain that the 555 Timer astable multivibrator is also an RC relaxation oscillator with the same basic principle of operation and recognise it in schematic diagrams
- Predict the output waveshape, frequency, amplitude, and absolute peak voltages of the two RC relaxation oscillators
- Recognise the 555 Timer astable multivibrator VCO circuit in a schematic diagram
- List the likely faults that can occur in the two RC relaxation oscillators
- Describe the effects of these faults on the performance of the two RC relaxation oscillators
- Use an oscilloscope to practise making measurements in oscillator circuits and to investigate the operation of an RC relaxation oscillator

Introduction

Naturally, not all oscillators output a sinewave. There's also a need for triangular wave oscillators and square and rectangular wave oscillators too. When a square/rectangular wave oscillator outputs a signal at levels that satisfy the input voltage requirements of a logic family series of ICs then the circuit is called a *digital oscillator* or *astable multivibrator*. This chapter introduces you to some digital oscillator circuits.

Revision of input voltages for the two logic levels

Before introducing you to some of the many digital oscillator circuits, it's necessary to clarify the what is meant by the requirement for digital oscillators to output signals "...at levels that satisfy the input voltage requirements of a logic family series of ICs...".

Recall from your earlier studies that TTL and CMOS logic circuits and devices use standardised ideal voltages to represent the two logic levels. For TTL, the ideal voltages are 0V and 5V for logic-0 and logic-1, respectively. And for CMOS, they're 0V and V_{DD} for logic-0 and logic-1, respectively. So square/rectangular wave oscillators only qualify as digital oscillators if the mark and space (that is, the logic-1 and logic-0) of the output signal correspond with these voltages.

That said, there's a little more to it. Recall that the operation of logic gates and devices isn't perfect and so the 0s and 1s are actually unlikely to be these ideal values. So, the inputs to regular TTL/CMOS logic gates/devices must be a little forgiving and accept a range of values near these two ideal numbers.

Table 1 below shows the range of allowable input voltage for a logic-0 (V_{IL}) and a logic-1 (V_{IH}) for readily available TTL sub-families and the CMOS 4000 series of devices.

Table 1

Specification	TTL sub-families including 74LS, 74AS and 74ALS	4000 series CMOS
Logic-0 input voltage range	0V to 0.8V	0V to $0.3\times V_{DD}$
Logic-1 input voltage range	2.0V to 5V	$0.7\times V_{DD}$ to V_{DD}

From the data in this table, we can see that a 4Vpp squarewave that has a lower peak of 0V and an upper peak of 4V (instead of 5V) would be accepted by all of these TTL subfamilies. And it would also be accepted by the CMOS 4000 series operating with a V_{DD} of 5V DC, but not for a device operating with a V_{DD} of 10V DC).

The CMOS crystal-controlled digital oscillator (or Pearce oscillator)

Consider the circuit involving a single NOT gate in Figure 1 below. When you think about the truth table of NOT gates, it's tempting to think that this circuit would oscillate. That's because, if the output is a logic-0, it would be fed directly back to the gate's input and inverted to produce a logic-1 on its output. In turn, this logic-1 would be returned to the input and inverted to produce a logic-0 on its output. And so on.

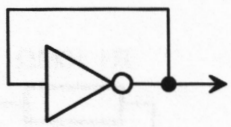

Figure 1 *Would this circuit oscillate?*

It's a cute idea and actually works for three cascaded NOT gates and other odd numbers of cascaded NOT gates. (As an aside, these circuits are call *ring oscillators* but they're seldom used commercially, if ever, because of the problems of obtaining an output with an accurate frequency.)

The circuit in Figure 1 doesn't oscillate (at least, not with an output that is a digital signal) because the natural frequency of oscillation (set by the gate's *propagation delay* specification) would exceed the gate's *maximum clock frequency* specification. (Refer to your Digital Electronics notes for more information on these two specifications.)

What's interesting about the NOT gate though, is what happens when a 10MΩ resistor is used to connect the output to the input as shown in Figure 2 below.

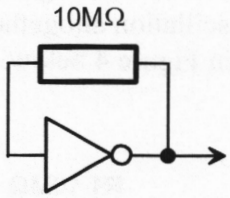

Figure 2 *A NOT gated biased to operate as an inverting amplifier*

The resistor forces both of the gate's input and output to sit at about half supply instead of at an acceptable voltage for either a logic-0 or a logic-1. In other words, the gate's input and output voltage rest in the transition zone between the two logic levels (which the gate's output voltage usually only ever passes through in normal operation) and the gate is said to be operating in its *linear* region. This means that the NOT gate has effectively become an inverting amplifier.

Usefully, the gain of CMOS NOT gates is very high (apparently, it's about 10,000) and this means that, when operated in its linear region, it can be used to implement the amplifier in a positive feedback closed-loop system.

To satisfy Barkhausen's second and third criteria, a positive feedback network is needed that introduces another 180° of phase shift at just one frequency. This is achieved using the positive feedback network from the Colpitts oscillator and this is shown in Figure 3 below.

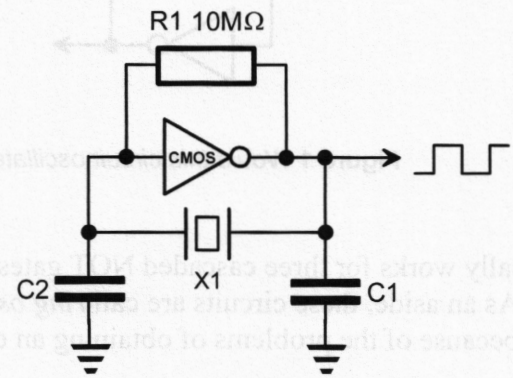

Figure 3 *A CMOS crystal-controlled digital oscillator*

As the circuit doesn't have any negative feedback, there is no way of controlling the NOT gate's gain and so the loop gain is much greater than one (it's about 1,000) and so the output runs away producing a heavily clipped sinewave that very closely resembles a squarewave.

The circuit's frequency of oscillation is equal to the crystal's operating frequency provided *C1* and *C2* are sufficiently large. However, connecting a load to this circuit risks changing the frequency of oscillation or halting oscillation altogether. So, the output is usually taken via a buffer or inverting buffer as shown in Figure 4 below.

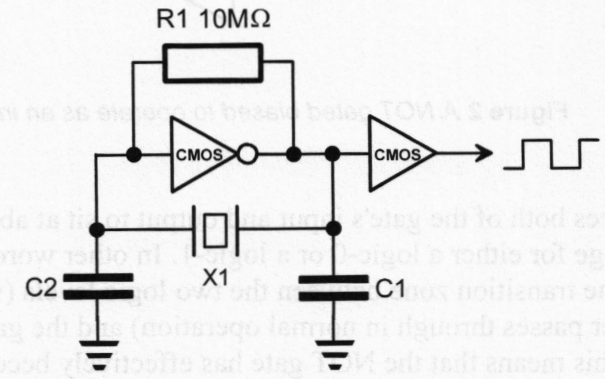

Figure 4 *The circuit in Figure 3 but with a buffered output to prevent loading from stopping oscillation*

Note: The circuits in Figure 3 and 4 do not work if implemented using TTL NOT gates. That's because their gain is not sufficiently high to overcome the positive feedback network's beta (which, you may recall, is 0.1) to produce a loop gain of greater than one.

A variation on the Pearce oscillator

There are many digital oscillator designs based on gates. A variation of the Pearce oscillator that can be implemented using either TTL or CMOS NOT gates is shown in Figure 5 below .

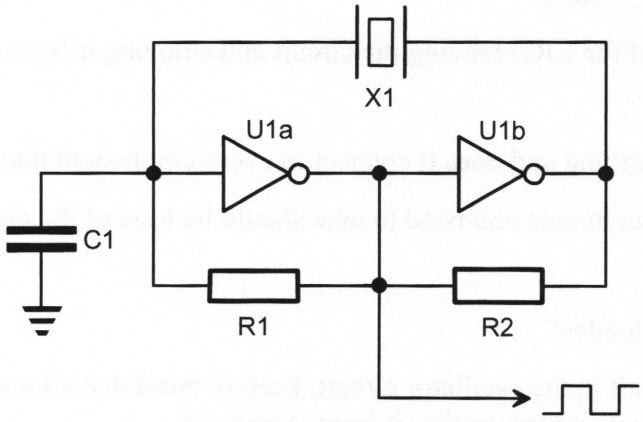

Figure 5 *Another crystal-controlled digital oscillator*

R1 and *R2* introduce a bias that forces the cascaded pair of NOT gates to operate in their linear region (that is, as a cascaded amplifier with a large gain). Together, the NOT gates introduce 360° of phase shift. The crystal, together with *C1* produces 0° of phase shift at the crystal's operating frequency. This satisfies Barkhausen's second and third criteria and so the circuit oscillates. But again, without any negative feedback, the oscillation runs away and so the output is a squarewave. The output is taken from between the NOT gates to prevent the load from connecting directly to the positive feedback path which could change the frequency of oscillation or prevent oscillation altogether.

Fault-finding the Pearce oscillator and similar digital oscillators

Before discussing specific fault-finding techniques for the Pearce oscillator and other digital oscillators that operate in the same way, it's important to again briefly revisit the questions you should ask yourself when you start:

- Is the loop still closed?

  It can be useful to perform a visual inspection of the circuit to identify any possible poor solder joints or physical damage to components or the circuit board.

- Is the oscillator actually faulty?

  To minimise the risk of the CRO loading the circuit and stopping it from oscillating, use an attenuated CRO probe.

- Is the power supply working and does it connect to every component that it should?

  The first voltage measurements you need to take should be tests of the amplifier's power supply connections.

- Is the oscillator being loaded?

  If you can't find the fault in the oscillator circuit, keep in mind that a fault elsewhere in the system may be loading it and preventing it from starting up.

As the Pearce and similar oscillators are crystal-controlled, you should expect the difference between the oscillator's theoretical and measured output frequencies to be extremely small (about 1Hz of error, or less, for every one million Hertz). If the error is larger than this, and you trust your instrumentation, then the components in the positive feedback network need checking.

If the circuit is not oscillating at all, the problem is probably **not** one of the components in the positive feedback network. That's because, for reasons discussed in previous chapters, one of these components will have had to change value substantially, or have completely failed altogether, for the circuit to stop oscillating which is less likely than other possibilities.

The more likely possibility is that the NOT gate has failed, or one of the NOT gates has failed if there is more than one in the circuit. These can be checked by logic-level tracing which you'll recall simply involves using a logic probe or DMM to check the logic levels on the inputs and outputs of the gates until you have found the faulty node. Once you have, one of the gates connected to the node is faulty. If more than two NOT gates have been used to implement the oscillator circuit, they'll almost certainly be inside the same IC. In which case, you don't need to determine which gate is faulty as the IC will need replacing anyway.

RC relaxation oscillators

Relaxation oscillators (also called astable multivibrators) are a class of digital oscillator that use feedback but don't rely on Barkhausen's Criteria for their operation. Instead, they use the feedback to compare the potential difference across a charging or discharging capacitor to one of two threshold voltages that, when crossed, reverses a switching device's output (so, flipping its output logic level) and reverses the capacitor's charging/discharging action.

There's a lot in that last paragraph that can be more easily understood using a circuit. There are literally dozens of relaxation oscillator designs but probably the simplest is the one that uses a NOT gain with hysteresis; the schematic symbol of which is shown in Figure 6 below.

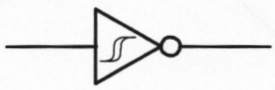

Figure 6 *A NOT gate with hysteresis (either TTL or CMOS)*

This chapter has already revisited the fact that regular logic gates (ie gates without hysteresis) have a range of input voltages that they will accept as a logic-0, a range of voltages that they will accept as a logic-1 and a range of voltages in between that belong to the transition zone. This can be represented graphically for the readily available TTL sub-families in Table 1 as shown in Figure 7 below.

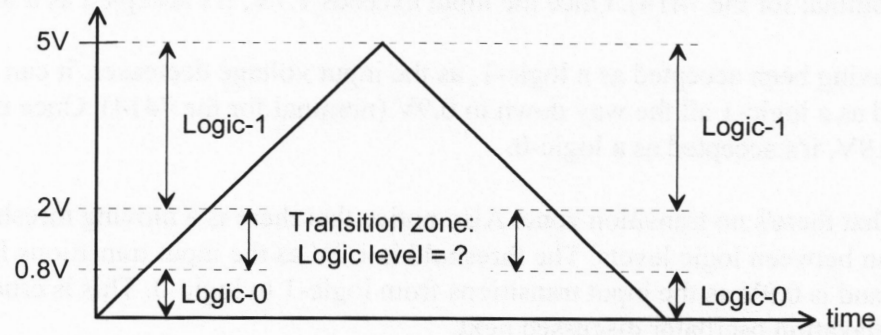

Figure 7 *The graph of input voltage to a regular TTL logic gate as it changes from 0V to 5V to 0V with indications of where the voltage lands in relation to the gate's ranges of acceptable input voltages*

The transition zone of regular logic gates is problematic because it's not possible to reliably determine whether voltages in this region will be accepted as a logic-0 or a logic-1 and so stable inputs at these voltages are best avoided. For circuits where this might be a problem, logic gates with an engineered *hysteresis* effect on the inputs can be used. The detail of how this is done need not be discussed here (the gates have a circuit on each input called a *Schmitt Trigger* which you can research online if you want to know more) but the gate's operation looks like Figure 8 below.

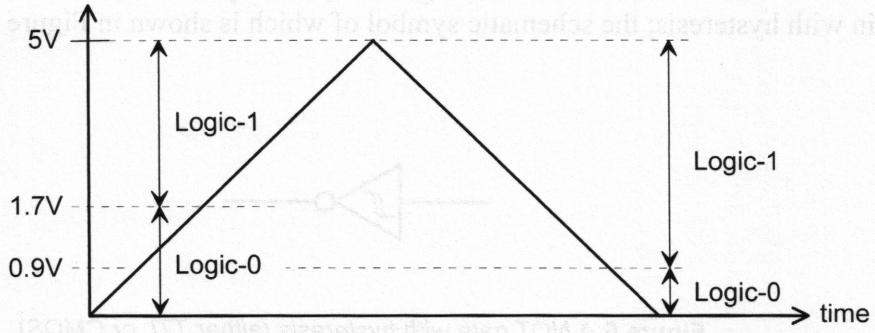

Figure 8 *The graph of input voltage to a TTL logic gate with hysteresis as it changes from 0V to 5V to 0V with indications of where the voltage lands in relation to the gate's ranges of acceptable input voltages*

For TTL logic gates with hysteresis, if the gate has already accepted an input as a logic-0 then, as the input voltage increases, it can do so and still be accepted as a logic-0 all the way up to the 1.7V (nominal for the 7414). Once the input exceeds 1.7V, it's accepted as a logic-1.

Then, having been accepted as a logic-1, as the input voltage decreases, it can do so and still be accepted as a logic-1 all the way down to 0.9V (nominal for the 7414). Once the input drops below 0.9V, it's accepted as a logic-0.

Notice that there's no transition zone. Also notice that there is a moving threshold for the transition between logic levels. The threshold is 1.7V as the input transitions from logic-0 to logic-1 and is 0.9V as the input transitions from logic-1 to logic-0. This is crucial to the operation of the relaxation oscillator discussed next.

Figure 9 below shows the NOT gate with hysteresis in Figure 6 having the threshold voltages described in Figure 8 (and explained in the paragraphs directly underneath) and used to implement an RC relaxation oscillator.

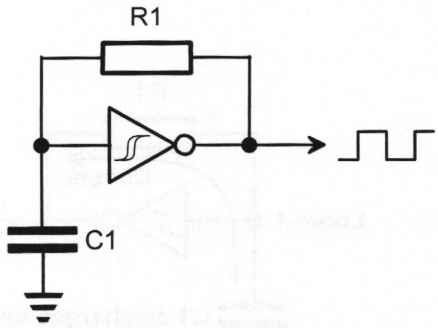

Figure 9 *An RC relaxation oscillator implemented using a NOT gate with hysteresis*

To understand the circuit's operation, let's assume that the circuit is off and capacitor is fully discharged and so has a potential difference of 0V. When the circuit is turned on, the 0V across the capacitor will be interpreted at the input of the gate as a logic-0 and so its output is a logic-1 (and represented by a voltage approaching the gate's supply voltage, let's assume 5V).

With 5V on gate's output and the capacitor connected to common (shown using the ground symbol here for convenience), current flows via the series combination of *R1* and *C1* and so the capacitor begins to charge towards the gate's supply voltage. This is shown in Figure 10 below.

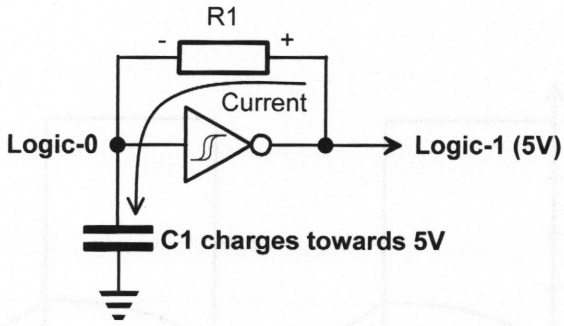

Figure 10 *The conditions around the circuit as C1 charges*

For the whole of the time that the potential difference across the capacitor is below 1.7V, the gate will treat the input as a logic-0 and so the output will remain a logic-1.

Once the potential difference across the capacitor exceeds 1.7V, the gate will treat the input as a logic-1 causing its output to switch to a logic-0 which will be represented by a voltage approaching 0V. Importantly, this means that the polarity of the potential difference across *R1* reverses and so current flows through it in the opposite direction sourced by *C1* and so the capacitor discharges. This is shown in Figure 11 below.

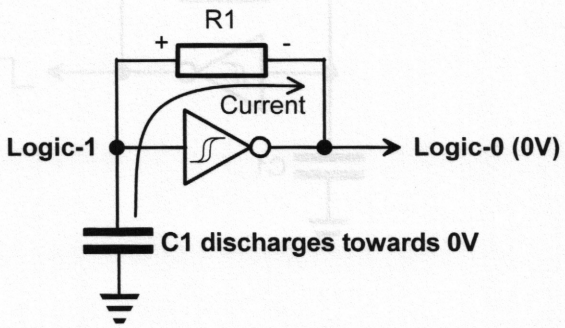

Figure 11 *The conditions around the circuit as C1 discharges*

Once the potential difference across the capacitor drops below 0.9V, the gate treats the input as a logic-0 causing its output to switch to a logic-1 and the whole process repeats producing an output that flips back and forth between logic-0 and logic-1 giving a digital signal.

The description of the operation of this circuit can complemented by a the graph in Figure 12 below which shows the potential difference across the capacitor time coincident with the NOT gate's output. Notice that the capacitor's potential difference has peaks at the NOT gate's threshold voltages per Figure 8 on page 5-8.

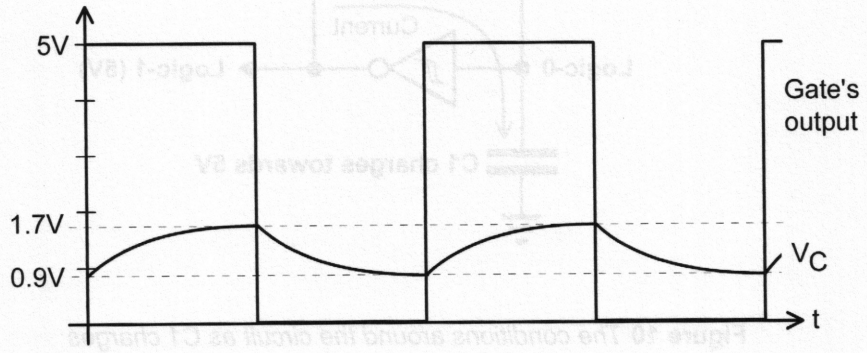

Figure 12 *The time-coincident graph of the cap's potential difference and the gate's output voltage*

Assuming the NOT gate is one from inside the 7414 IC, the frequency of oscillation is calculated using the equation:

$$f_o = \frac{0.978}{RC}$$

It requires more knowledge of math than is expected of Certificate III students to explain how this equation is derived. (And, if your author is honest, it requires more knowledge of math than he is confident about reliably teaching to students!)

For the more mathematically inclined students, it's a simplification of the equation...

$$f_o = \frac{1}{RC \ln\left(\frac{V_{OH}-V_{T-}}{V_{OH}-V_{T+}} \times \frac{V_{T+}}{V_{T-}}\right)}$$

...where V_{OH} is the gate's specified output voltage for a logic-1 (3.4V for the 7414), V_{T+} is the gate's specified upper threshold voltage (1.7V for the 7414) and V_{T-} is its specified lower threshold voltage (0.9V for the 7414). Research online if you're interested to know more.

The 555 Timer IC astable multivibrator

An IC that was once extremely popular, especially with hobbyists, teachers and students is the NE555 Timer. It consists of a BJT, three 5k resistors connected in series, two comparators (with connections to the voltage divider), an RS flip flop and a buffer.

What might surprise you about this device is that it's an incomplete circuit and the addition of some external components is always necessary to make it do something useful. It was designed this way by its inventor, Hans Camenzind, to maximise the flexibility of how the chip could be used and even he has been extremely surprised by how many circuits this humble chip has been cleverly used to implement.

Figure 13 below shows the 555 Timer IC with external components connected to it to implement an RC relaxation oscillator.

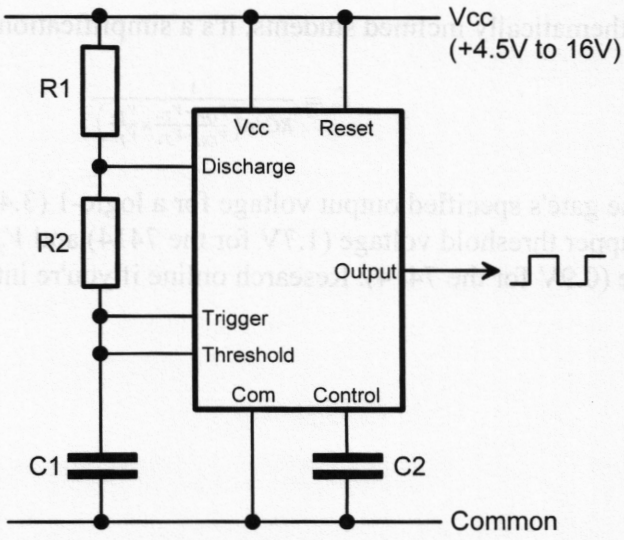

Figure 13 *The 555 Timer IC with external components used to configure the device to implement an RC relaxation oscillator*

Without going into the internal workings of the 555 Timer IC, the operation is very similar to the circuit involving the NOT gate with hysteresis described earlier. When the output voltage is high, the capacitor *C1* charges up. When the potential difference across *C1* reaches two thirds of *Vcc*, the device is prompted into reversing its output and so it goes low. When the output voltage is low, the capacitor discharges. When the potential difference across *C1* reaches one third of *Vcc*, the device is prompted into reversing its output and so it goes high again, and the process repeats.

The description of the operation of this circuit can complemented by a the graph in Figure 14 below which you'll notice is nearly identical to Figure 12 on page 5-10 (except for the threshold voltages). This is how RC relaxation oscillators work.

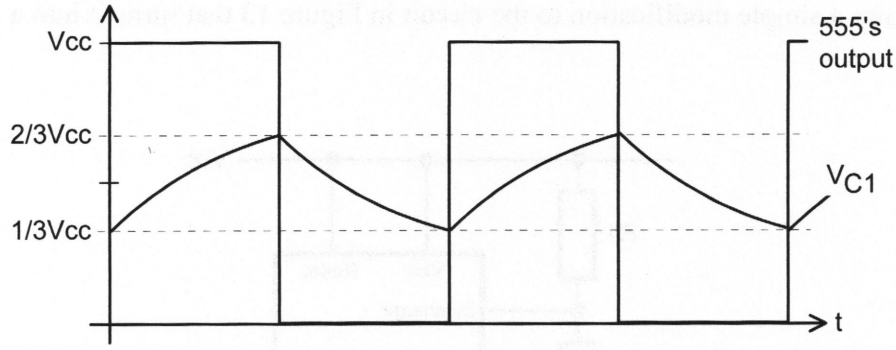

Figure 14 *The time-coincident graph of the timing cap's potential difference and the 555's output voltage*

This circuit's frequency of oscillation is calculated using the equation:

$$f_o = \frac{1.44}{(R_1+2R_2)\times C1}$$

How this equation is derived is a little easier to understand than the equation on page 5-11 but it's not necessary to discuss it here. Research online if you want to know more - There's loads of information on the internet on the 555 Timer IC including the nitty-gritty of how this circuit works.

Your author is a little uncomfortable with teaching students about this 50 year old device in a modern Unit on oscillators as there are other ICs used to implement digital oscillators that out-perform this circuit in terms of maximum output frequency, accuracy and stability. The MIC1555 and MIC1557 are popular examples and cost a little less than the 555 Timer IC (though, to be fair, they're based on the original NE555 Timer IC architecture). The LTC6903 is a device that's completely different to the 555 Timer and more expensive but is programmable for outputs from 1kHz to 68MHz!

Another reason your author is unenthusiastic about this device is because microcontrollers can be used to implement most, if not all, of the circuits that the 555 has ever been used to implement and probably every bit as cheaply, probably using fewer components, almost certainly with more reliable operation, and definitely with lower power consumption requirements (which is essential for battery operated equipment). With that said, using a microcontroller does require specialist software (called an IDE) and coding experience that is not needed for the implementation of 555 Timer circuits.

While there's a variety of dedicated digital oscillator chips on the market, there are very few digital voltage-controlled oscillator (VCO) chips with a centre frequency under 10MHz and none with a centre frequency under 1MHz (that your author could find quickly). Digital VCO chips can be expensive too. So, the 555 Timer IC is a particularly good solution for implementing a low cost, relatively low frequency digital VCO if you want to avoid using a microcontroller. Figure 15 below shows a simple modification to the circuit in Figure 13 that turns it into a digital VCO.

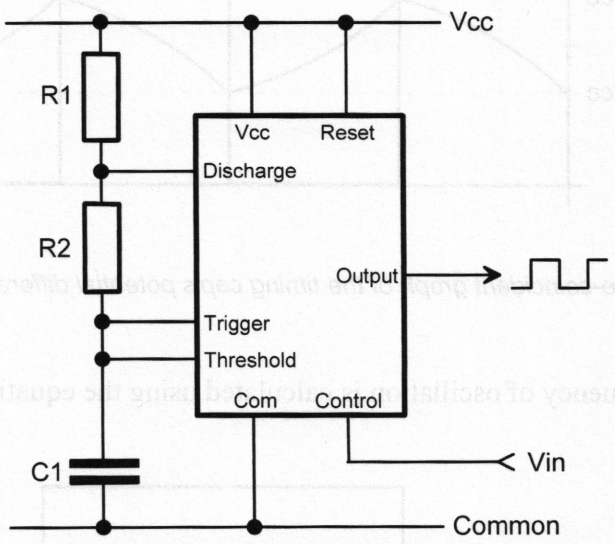

Figure 15 *The 555 Timer IC used to implement a digital VCO*

Here, the voltage on the IC's control input (*Vin*) overrides the internally determined threshold voltages that prompt the IC's output to change state. In the process, instead of the lower and upper thresholds being $\frac{1}{3}$ and $\frac{2}{3}$ of *Vcc*, they're $\frac{1}{2}$ of *Vin* and *Vin*, respectively. This is shown in Figure 16 below for illustration with *Vin* set to a relatively small DC voltage compared to the *Vcc*.

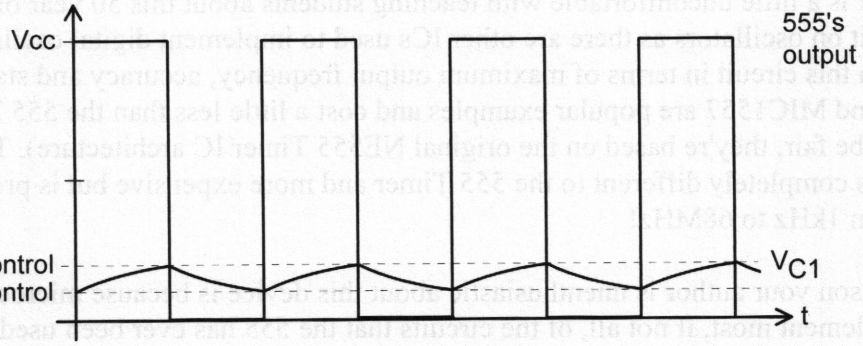

Figure 16 *The time-coincident graph of the timing cap's potential difference and the 555's output voltage for a relatively small DC voltage on the IC's control input*

To appreciate how this works, suppose *Vin* is 1V. The capacitor would charge and discharge between 1V and 0.5V respectively which is a difference of 0.5V. But, if *Vin* is 10V then the capacitor would charge and discharge between 10V and 5V respectively which is a difference of 5V. The greater difference between the threshold voltages, the longer it takes the capacitor to reach them and so the period of the waveform increases, reducing the frequency of oscillation.

(Note: You've been taught that the voltage that the capacitor is charging to, or discharging from, has no bearing on the time it takes the capacitor to charge/discharge. That's because, any increase in voltage causes a corresponding increase in current which increases the rate of charge and thus compensates for the capacitor needing to reach, or drop down from, a higher voltage. However, this fact is not applicable here because the arrangement inside the IC cannot be simplified to a simple series RC circuit connected to a DC voltage source. Things are a little more complex inside the 555 Timer and, importantly, the current through the capacitor is fairly constant for any value of *Vin*.)

This circuit variation exemplifies the point made earlier about microcontrollers doing a better job. Varying the *Vin* varies the output signal's frequency and the circuit definitely works. However, varying the *Vin* also varies the output signal's duty cycle. So, as clever as the circuit is, if you needed a digital VCO with a fixed duty cycle, you can't use it. A quick search on the internet for an alternative 555 Timer VCO circuit design without this problem appears to confirm this claim as none were found. You can definitely write code for a microcontroller to avoid this problem if one were used instead. (And interestingly, on one forum where someone has asked about this very issue, someone else who designs circuits has suggested using a microcontroller instead of the 555 Timer!)

Fault-finding RC relaxation oscillators

Once again, before discussing specific fault-finding techniques for RC relaxation oscillators, it's important to ask the relevant questions when you start:

- Is the power supply working and does it connect to every component that it should?

  The first voltage measurements you need to take should be tests of the amplifier's power supply connections.

- Is the oscillator being loaded?

  If you can't find the fault in the oscillator circuit, keep in mind that a fault elsewhere in the system may be loading it and preventing it from starting up.

As the output frequency of RC relaxation oscillators is controlled by one or more resistors and a capacitor, you would expect there to be a difference between the oscillator's theoretical and measured output frequencies. That said, the error shouldn't be greater than tolerances of the resistors and capacitor used. If it is, it would likely be due to component value drift and, in that case, you would definitely check the timing capacitor first if it's electrolytic (aluminium oxide) as these types of caps can readily drift in value or become leaky with age and/or extended exposure to higher temperatures.

Similarly, if the circuit is not oscillating at all and the timing capacitor is electrolytic (both types) it would be worth checking it first. Charging a leaky aluminium oxide electrolytic cap is like trying to fill a bucket with a hole in it. This would mean that the cap's potential difference can't reach one or both of the threshold voltages that prompt the IC's output to change state and so there would be no oscillation. Tantalum oxide electrolytic capacitors generally don't go leaky but they're somewhat sensitive to over-voltages and go short-circuit when they fail, preventing oscillation.

If the capacitors in the circuit are some non-electrolytic type (like polyester or ceramic), the problem is probably the IC itself. The currents through the components that set the timing are small and so they don't work hard and are much less likely to fail than the IC.

Skill practice 5

Practise measuring key voltages in digital oscillator circuits using an oscilloscope

This exercise is practise for the sorts of skills you may be required to perform in a practical test. Remember, in any practical tests you'll be working alone so make sure that you can perform all the steps. It should take you about 1¼ hours to complete this exercise.

Equipment

- Emona Trainer
- 74LS14 hex NOT gate with Schmitt Trigger input
- 4049 hex NOT gate
- 1kΩ ¼W resistor
- 10MΩ ¼W resistor
- 22nF capacitor
- two 560pF capacitors
- 32.768kHz crystal
- BNC to alligator-clip lead
- hook-up wire
- wire strippers

Remember:

Follow TAFE NSW WHS guidance at all times!

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Work tasks

1. Read your WHS responsibilities at the top of the form below. Then conduct a WHS risk assessment and record your findings in the space provided.

Responsibilities of students under the Model WHS Act: s28

- Take reasonable care for your own health and safety by working safely at all times
- Take reasonable care to ensure that your acts or omissions don't put the health and safety of others at risk
- Follow all TAFE NSW WHS guidance and comply with all reasonable instructions from TAFE NSW staff to assist them in complying with the TAFE NSW WHS requirements
- In addition to the above, you must:
  - use and maintain machinery, tools and all other equipment properly and safely
  - ensure that your work area is free of hazards
  - notify a TAFE NSW staff member of actual or potential hazards
  - wear/use prescribed safety equipment
  - take notice of any safety signs and adhere to their instructions

Risks involved in this activity include:	**Control measures:**
Trip hazards (eg students bags) Objects dropped on feet (while equipment is taken to and from workbenches).	Move bags and other objects from walkways Plan lifting of equipment
Others: _____	Other: _____
_____	_____
_____	_____

My signature here indicates that I have read and understand my responsibilities under the Model WHS Act s28 (detailed above). I have also conducted a risk assessment before undertaking this activity and have identified measures to control these risks and have implemented them.

Signature: _____ Date: _____

2. Gather the equipment needed for this exercise.

3. Wire the circuit of Figure 1 below using the 74LS14's pinout provided.

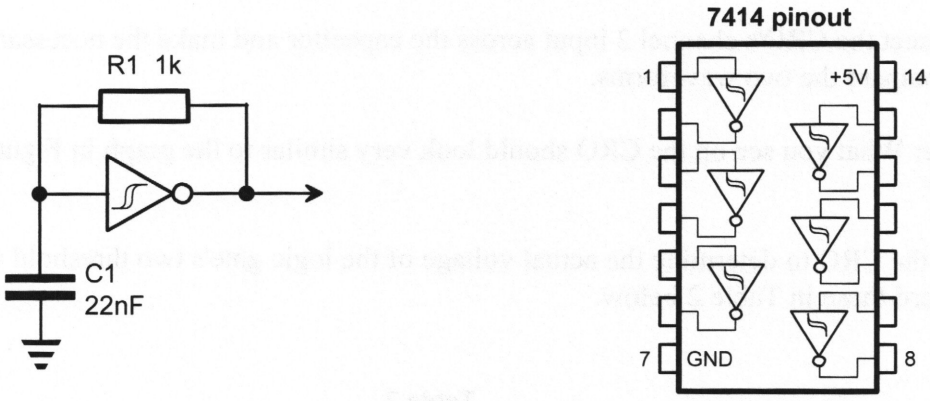

Figure 1

4. Calculate the circuit's theoretical frequency of oscillation (f_O). Record your value in Table 1 below.

5. Turn on the power supply to the circuit.

6. Connect one of the CRO's inputs to the circuit's output and adjust it as necessary.

   Self-check: If your circuit is oscillating you should see a squarewave. If it not, check your wiring and the supply to the IC's *Vcc* and *GND* pins before calling the teacher for assistance.

7. Accurately measure the output signal's period and use this to determine the frequency of oscillation. Record your measurement in Table 1 below.

Table 1

Theoretical *fo*	
Measured *fo*	

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Question 1
The two figures in Table 1 are unlikely to be the same. What's the main reason for this?

8. Connect the CRO's channel 2 input across the capacitor and make the necessary adjustments to compare the two waveforms.

   Note: What you see on the CRO should look very similar to the graph in Figure 12 on page 5-10.

9. Use the CRO to determine the actual voltage of the logic gate's two threshold voltages. Record these in Table 2 below.

Table 2

Lower threshold voltage (V_{T-})	
Upper threshold voltage (V_{T+})	

Question 2
Compare these threshold voltages with the values given in Figure 12 on page 5-10. Why might they not be exactly the same?

The teacher needs to check your work at this point...

10. Wire the circuit in Figure 2 below.

Note 1: You must use the CMOS 4049 for this circuit and **not** the TTL 74LS14.

Note 2: Use 5V for the IC's V_{DD}.

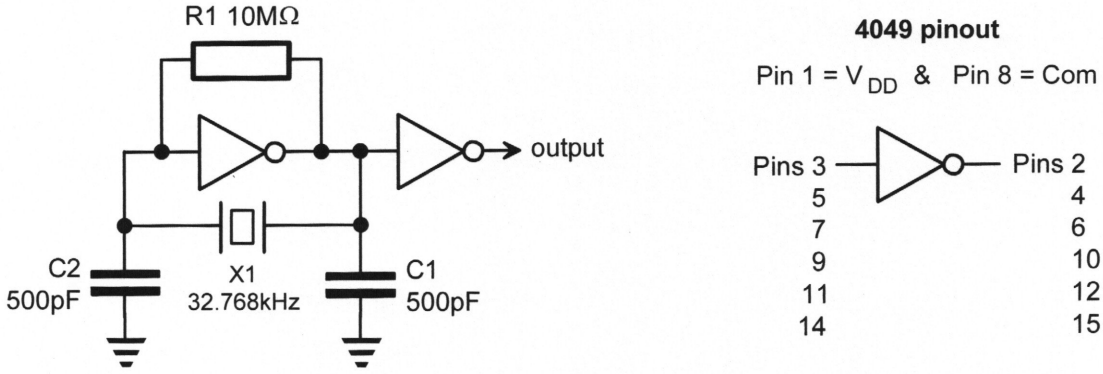

Figure 2

11. Measure the output signal's period and use this to determine the frequency of oscillation. Record your measurement in Table 3.

Table 3

Measured *fo*	

Question 3
What component or components set the circuit's frequency of oscillation?

Question 4
What is the purpose of the second NOT gate?

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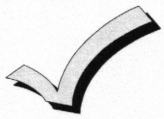

The teacher needs to check your work at this point...

Review questions

Answer these questions to check your understanding of what you have learnt for this chapter. Doing this will also help to prepare you for the tests.

1. In what way is the output of digital oscillators different to the generic square/rectangular wave output of function generators?

Questions 2 to 7 refer to the circuit in Figure 1 below

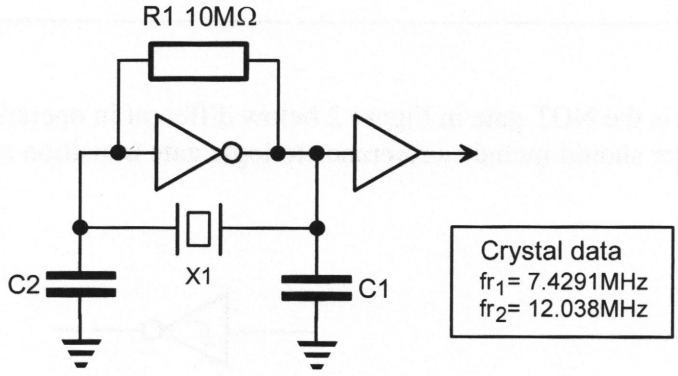

Figure 1

2. Give one of the two names for this circuit.

3. What is the output signal's shape?

4. What is the output signal's frequency?

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5. What logic family must be used for the NOT gate for this circuit to work as an oscillator?

6. What is the output signal's peak-peak voltage? Assume the IC's V_{DD} is 12V.

7. What component in Figure 1 is most likely faulty if the circuit is not outputting a signal but checks of the power supply voltage and connections are all ok? Explain your answer.

8. How is the NOT gate in Figure 2 below different in operation to regular NOT gates? Your answer should include a reference to logic gate transition zones.

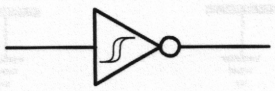

Figure 2

Questions 9 to 13 refer to the circuit shown in Figure 3 below

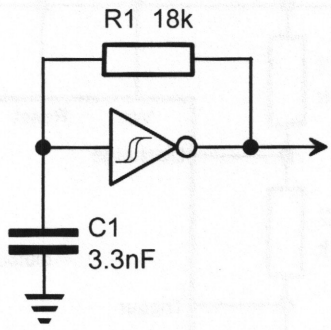

Figure 3

9. What is the name of this circuit?

_____

10. What is the output signal's shape?

_____

11. Calculate the output signal's frequency. **Note:** Assume the NOT gate used is one inside the 7414.

_____

_____

_____

12. What logic family or families can be used for the NOT gate for this circuit?

_____

13. What component in Figure 3 is most likely faulty if the circuit is not outputting a signal but checks of the power supply voltage and connections are all ok?

_____

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Questions 14 to 18 refer to the circuit shown in Figure 4 below

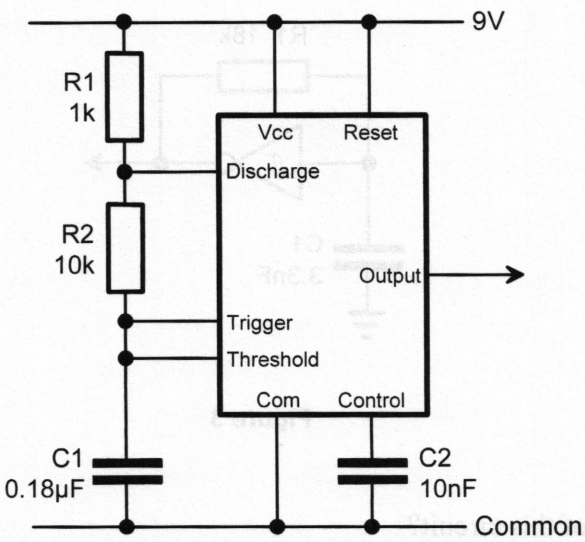


Figure 4

14. What is the name of this circuit?

_____

15. What is the output signal's shape?

_____

16. What is the output signal's peak-peak voltage?

_____

17. Calculate the output signal's frequency.

_____

_____

_____

18. What component in Figure 4 is most likely faulty if the circuit is not outputting a signal but checks of the power supply voltage and connections are all ok?

_____

Appendix Frequency synthesis using the PLL

Purpose To develop your ability to recognise and understand the operation of the phase-locked loop and frequency synthesis.

Objectives At the end of this section you should be able to:

- Draw the block diagram of the analog and digital phase-locked loops
- State the basic operation of each block in a PLL
- Define the term *lock* in terms of PLL operation and the relationship between the PLL's input and output signals
- Explain what happens to a locked PLL's output when either the input signal or the VCO's output signal changes frequency or phase (due to drift or some other reason)
- Briefly explain what *frequency synthesis* involves
- State the advantage of frequency synthesis compared with other methods of achieving a crystal-controlled variable frequency oscillator (VFO)
- State the two modifications required to force the PLL to implement frequency synthesis

Introduction

A *variable frequency oscillator* (VFO) is an oscillator with output frequency that can be changed. As you have seen with both the LC and crystal-controlled sinewave oscillators and the crystal-controlled digital oscillators, changing an oscillator's output frequency can be done by varying the value of a series capacitor (per the Clapp Oscillator). This is problematic though because capacitors drift in value (due to temperature changes, age, etc) and so the output frequency can drift. For crystal-controlled oscillators, the drifting capacitor negates the advantage of using a crystal in the first place.

To avoid this problem for crystal-controlled VFOs, making the frequency of oscillation variable was once achieved by simply changing the crystal frequency. This was done by desoldering the original part and replacing it or, more likely, selecting different crystals using a switch. Neither option is ideal.

These days, the most common method of implementing a crystal-controlled VFO involves a process called *frequency synthesis* and is usually implemented using the *phase-locked loop* (PLL).

The phase-locked loop (analog)

The phase-locked loop (PLL) was developed in the early 1930s. However, its profound complexity meant that its use was impractical for most applications until the advent of the integrated circuit. These days the PLL is widely used in all manner of applications and so you'll hear about this circuit again and again.

The basic block diagram of a PLL is shown in Figure 1 below.

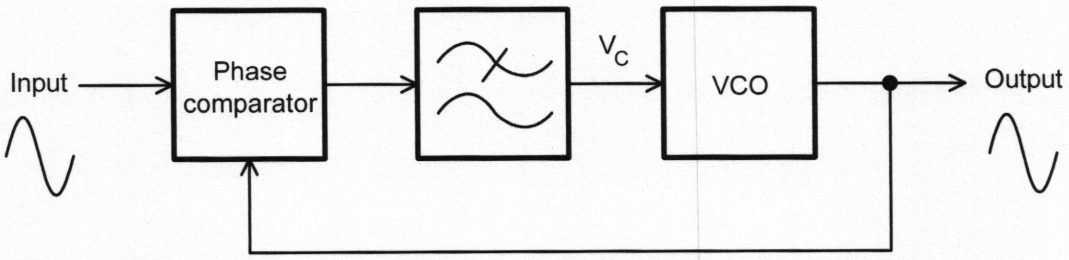


Figure 1 *The basic block diagram of a PLL*

The following notes explain the operation of each functional block before providing an explanation of the circuit's overall operation.

- The phase comparator

  As its name implies, this circuit compares the phase relationship between the signals on its two inputs. Following this, the phase comparator outputs a relatively high frequency sinewave and an effective DC voltage that is proportional to the phase difference between the its two inputs.

- The low-pass filter

  The low-pass filter (LPF) is included to reject the "relatively high frequency sinewave" on the phase comparator's output and allow only the effective DC voltage to reach the VCO's control input. As such, this DC voltage is called the *control signal* (V_C in this case).

- The VCO

  The voltage-controlled oscillator (VCO) is a circuit that has been introduced to you earlier in this subject. It is an oscillator with an output that can be made to change frequency in response to an input voltage. A positive voltage makes the oscillator's output frequency increase and a negative voltage makes it decrease (or vice versa).

Circuit operation

To explain the circuit's operation (not an easy task!), let's start with a PLL that has a broken loop as shown in Figure 2 below.

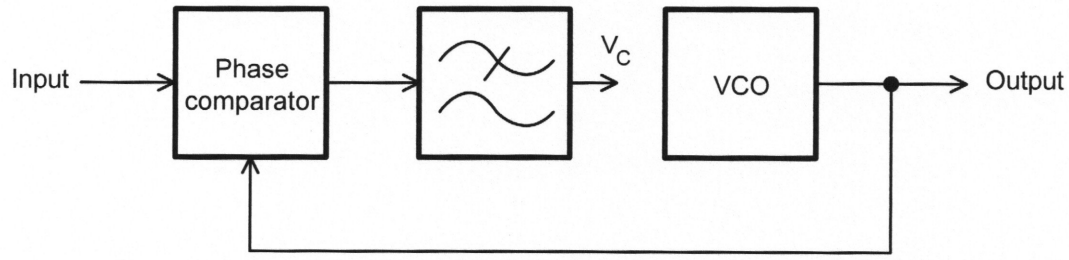


Figure 2 *The PLL in Figure 1 but with a broken loop*

Suppose that the PLL's input frequency is exactly 100kHz and, by chance, the VCO's output frequency is also exactly 100kHz and exactly +90° (or -90°) out of phase. This means that the phase comparator's DC output voltage is 0V (why is not explained here). So, if the loop is remade by connecting the LPF's output to the VCO's input this voltage would not cause any change on the VCO's output.

Now returning to a broken-loop PLL, suppose that the VCO's output frequency changes (but not too much). There would be a difference in frequency between the phase comparator's two inputs that simultaneously produces a rolling phase difference. This in turn produces a changing DC voltage on the phase comparator's output that readily passes through the LPF. So if the loop is remade, this changing DC voltage would cause the VCO's output frequency to go up and down.

As the VCO's output frequency goes up and down, at some point it must output a sinewave with exactly the same frequency as the phase comparator's input and be plus or minus 90° with it. At that moment, the phase comparator's DC output voltage stops changing and so the VCO's output frequency sticks at that frequency and phase relationship.

This condition is called *lock* and, once achieved, any changes in either the phase comparator's input voltage or the VCO's output immediately causes a change in the control voltage that forces the VCO's output to change to match the input frequency and regain lock.

[Naturally, there is a limit to this. For every PLL there is a range of frequencies over which the PLL can achieve lock and outside this range lock is impossible.]

This ability of the PLL's output to match or "track" the input frequency might not seem like much but it's tremendously useful. And as mentioned before, you'll hear of this circuit being used in all sorts of applications.

Section 5 (continued)

9. RC relaxation oscillator implemented using a NOT gate with hysteresis

10. Digital squarewave

11. $f_o = \frac{0.978}{RC}$

    $f_o = \frac{0.978}{18k \times 3.3nF}$

    $f_o = 16.46kHz$

    Note: The equation above is only valid if the circuit implemented using one of the NOT gates inside the 7414 IC.

12. This circuit will work with either TTL or CMOS provided the NOT gate has hysteresis.

13. The balance of probability here is the NOT gate. The exception would be if the capacitor is electrolytic, in which case you would check this first using an LCR meter because it's easier to remove a cap from a circuit board than an IC.

14. 555 Timer astable multivibrator

15. Digital squarewave

    Note: The waveform's duty cycle is a fraction over 50% so you could argue that it's actually a rectangular wave.

16. 9Vpp (but not ±4.5Vp).

17. $f_o = \frac{1.44}{(R_1+2R_2)\times C1}$

    $f_o = \frac{1.44}{[(1k+(2\times 10k))\times 0.18\mu F]}$

    $f_o = 381Hz$

18. For this fault, it's likely the 555 Timer IC. **But** although the timing capacitor (*C1*) is 180nF, its value has been given as 0.18µF. This would imply that the cap is electrolytic because it's very common practice in our industry to specify electrolytic caps in µF even when they could be better specified either in nF (for values below 1µF) or mF (for values of 1,000 µF and above). So, in this case, a visual inspection of the capacitor is needed to identify its type. If it's electrolytic, then you would probably be better off testing it first before replacing the 555 IC.

The phase-locked loop (digital)

The PLL can be implemented as a digital circuit - That is, with a pulse train for the input and output signals. The block diagram is identical but the interesting thing is that a simple EXOR gate can be used as a phase comparator. The digital PLL is shown in Figure 3 below.

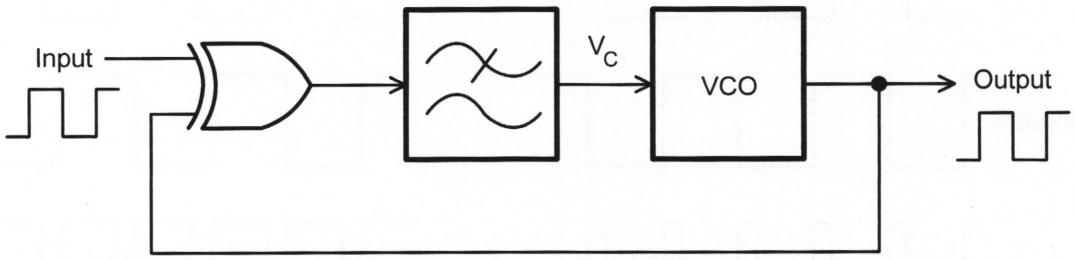


Figure 3 *The digital PLL*

How can an EXOR gate act as a digital phase comparator? To answer this question, consider the EXOR gate's truth table shown in Table 1 below.

Table 1 *Truth table for an EXOR gate*

Inputs		Output
B	**A**	**Z**
0	0	0
0	1	1
1	0	1
1	1	0

As you can see, when the logic levels on the EXOR gate's inputs are the same (either both logic-0 or both logic-1) the gate outputs logic-0 (which is zero volts). And when the gate's inputs are different it outputs a logic-1 which is 5V.

So, when two pulse trains on the EXOR gate's inputs are exactly the same frequency and phase, it must output a continuous logic-0. However, any differences in phase and/or frequency between the two signals must result in instances when the inputs are different logic levels and so the gate's output must pulse high during that time.

Importantly, the greater the difference in frequency or phase between the signals, the longer the pulses to logic-1 become. This is shown in Figure 4 below using two signals that are the same frequency but with different fixed amounts of phase shift. The dotted line in the output pulse train shows the relative size of the DC component that makes up the signal.

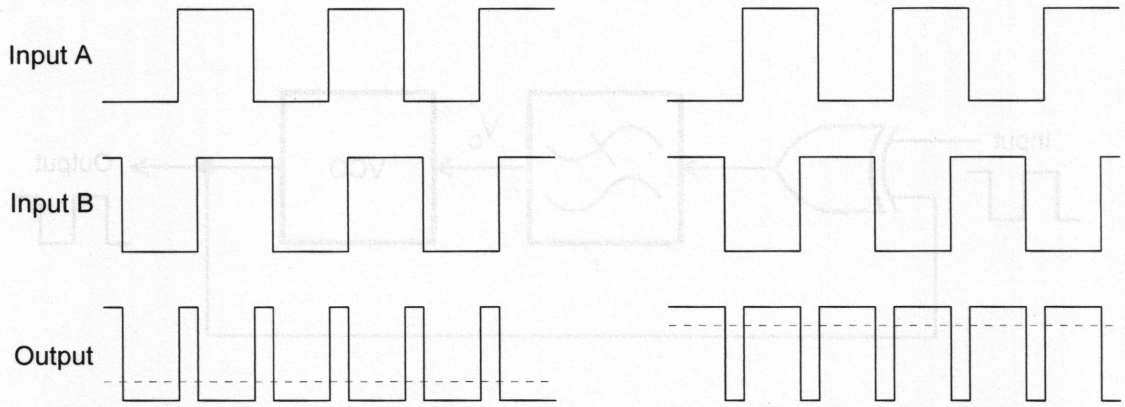


Figure 4 *The output of an EXOR gate for pulse trains on its inputs that are the same frequency but different (fixed) phase*

Linking the operation of the EXOR gate to the operation of the digital PLL, if lock has been achieved, the pulse train on the EXOR gate's output has a fixed pulse width. However, the moment the PLL's input signal or the VCO's output signal changes frequency, the width of the pulses changes. This in turn changes the size of the DC component that makes up the pulse train which is passed to the VCO via the low-pass filter causing the VCO's output frequency to change in such as way as to regain lock.

Frequency synthesis using the PLL

Generally speaking, frequency synthesis involves generating a reference signal (analog or digital) then connecting it to the input of a circuit that uses it to generate another signal at a frequency that is a multiple (or sub-multiple) of the reference. Frequency synthesis is ideal for implementing a crystal-controlled VFO because only one crystal is needed (for the reference) but any number of equally stable output frequencies can be produced without having to change crystals.

Figure 5 below shows a digital PLL modified to implement frequency synthesis. As you can see, a crystal-controlled oscillator is used to generate a *reference* signal that is connected to the PLL's input. A frequency divider in the feedback path is also a necessary modification. A divide-by-2 divider is shown in this example but it can be other values.

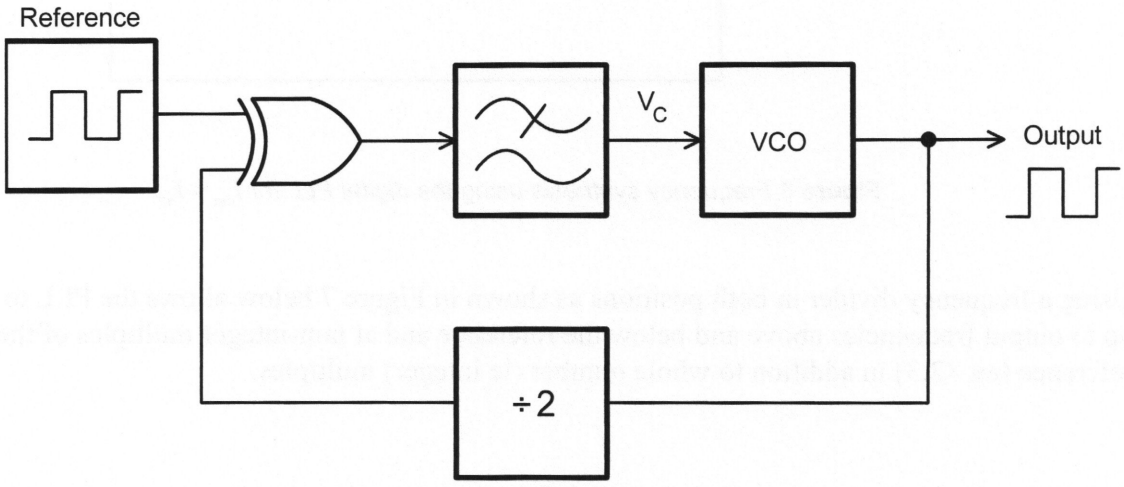


Figure 5 *Frequency synthesis using the digital PLL*

Now, a PLL with output a frequency that is different to its input sounds like a complete contradiction to how the PLL works. However, the key to understanding frequency synthesis using the PLL is the phase comparator's operation. The phase comparator is not concerned with the actual frequency of the VCO's output - It is only concerned with ensuring that its two inputs are the same frequency (and the phase shift is ±90°). Recall that once this is achieved (ie lock), the phase comparator's effective DC output voltage stops changing and so the VCO's output frequency stop changing.

So, the divide-by-2 frequency divider in the feedback path in Figure 5 above effectively "tricks" the phase comparator in to believing the VCO's output is half the reference frequency and so it generates a corresponding error signal. This in turn forces the VCO's output frequency to increase. When the VCO's output frequency is twice the reference, the phase comparator's two inputs are the same frequency and lock is achieved. Clever?

The frequency division can be achieved in a number of ways including using a counter, a shift register or a programmable device like a PIC. Of course, changing the division factor in the feedback loop changes the output frequency. For example, ÷3 gives an output frequency three times the reference, ÷4 gives an output that is four times the reference and so on.

Putting the frequency divider between the reference and the PLL's input as shown in Figure 6 below allows the PLL to be set up to output frequencies below the reference.

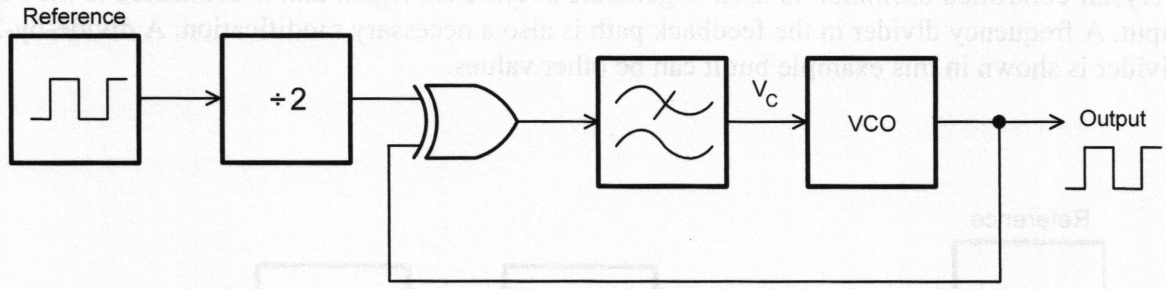


Figure 6 *Frequency synthesis using the digital PLL for $f_{out} < f_{ref}$*

Using a frequency divider in both positions as shown in Figure 7 below allows the PLL to be set up to output frequencies above and below the reference and at non-integer multiples of the reference (eg ×2.3) in addition to whole number (ie integer) multiples.

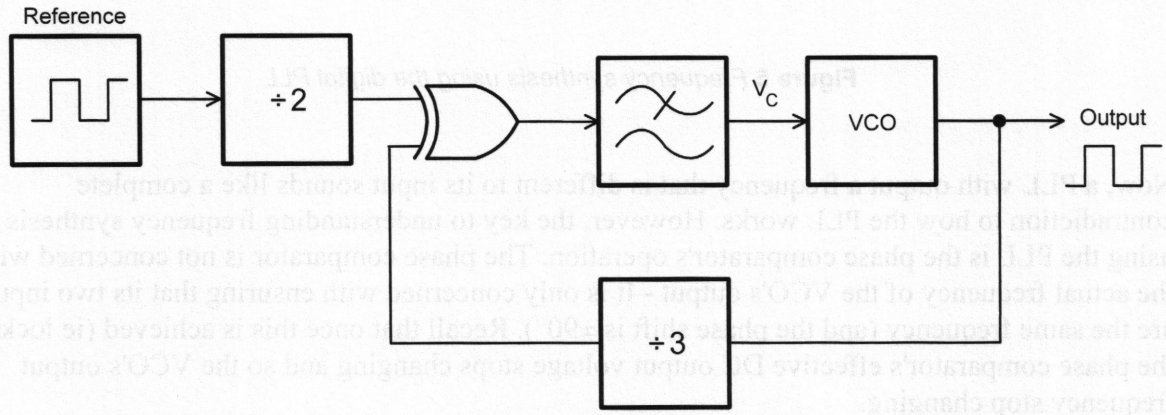


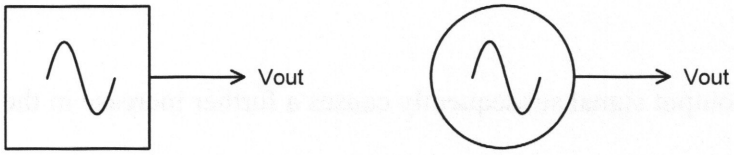
Figure 7 *A "fractional" PLL*

Answers to Review Questions

Section 1

1. An oscillator is a circuit that produces an AC waveform at its output with no input other than a DC power supply.

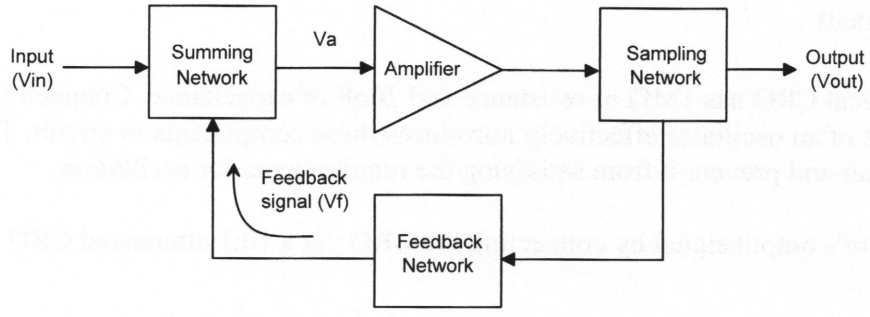
2.



3. Examples include:
   Clocks and watches
   Computers (or anything microprocessor or microcontroller controlled)
   Gaming machines
   VCRs
   DVD players
   CD players
   Radio and television transmitters
   Radio and television receivers
   Mobile phones
   Signal generators

4. A linear power supply (in other words, a power supply with shunt or series regulation).

5.



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Section 1 (continued)

6. The summing network adds the input signal and feedback signal together.
   The amplifier amplifies the addition of the input signal and the feedback signal.
   The sampling network takes a sample of the output voltage or current and feeds that to the input of the feedback network.
   The feedback network modifies the sample of the output voltage to produce a feedback signal.

7. Beta network

8. Regenerative feedback

9. Because any increase in the output signal subsequently causes a further increase in the output signal.

10. Positive feedback keeps increasing the input voltage to the amplifier (*Va*) and hence the output voltage (*Vout*) in a process that can spiral out of control or "run away".

11. Positive feedback

12. The loop gain of the system must be equal to or greater than 1
    The loop phase shift must be 0° or 360°
    The feedback network must be frequency selective

13. Noise on the input of the closed-loop system contains small voltages at every frequency in the electromagnetic spectrum. One of those signals will satisfy Barkhausen's Criteria and, although it will be extremely small, regeneration will quickly cause it to appear as a larger signal at the output of the oscillator.

14. 0.75

15. No. It's below 1 when the loop gain of the system must be equal to or greater than 1.

16. $\frac{1}{3}$ (or 0.3333 rounded)

17. The input to a typical CRO has 1MΩ of resistance and 20pF of capacitance. Connecting a CRO to the output of an oscillator effectively introduces these components to circuit. This can upset the circuit and prevent it from satisfying the requirements for oscillation.

18. Check the oscillator's output signal by connecting the CRO via a 10:1 attenuated CRO probe.

19. i) Check that the power supply is working and that both supply and common are connected to every component in the circuit.
    ii) Look for an open-circuit especially in the positive feedback loop due to a dry joint or cracked track.

Section 2

1. Wien-bridge oscillator

2. Because it produces a sinewave with very low amounts of distortion (which is the main advantage of this circuit over other sinusoidal oscillators).

3. $fo = \frac{1}{2\pi RC}$

   $fo = \frac{1}{2\pi \times 10k\Omega \times 1nF}$

   $fo = 15.92kHz$

   Note: It's interesting to contrast this figure with the answer to Question 2 which asked you to calculate the f_O of the RC Phase Shift oscillator implemented using the same component values in the positive feedback network. The difference occurs, of course, because the two equations for calculating f_O are similar but different.

4. 0°

5. 0°

6. The op amp's phase shift is 0° and the positive feedback network's phase shift is 0° making the total phase shift 0°.

7. Lead-lag network.

8. 1/3 (or 0.3333 rounded to four significant figures).

9. 30kΩ (Note: if you worked it out to be 45kΩ then you've used the voltage gain equation for an inverting amplifier!)

10. The oscillator won't start up.

11. PTC

12. The thermistor's value is chosen so that initially its value is low enough to provide a closed-loop gain for the op amp that is greater than 3 (making the loop-gain greater than 1).

13. Once the circuit starts oscillating the current through the thermistor warms it up and its resistance increases, lowering the op amp's gain preventing regeneration from running away.

14. The op amp is faulty (there's a short-circuit or very low resistance path from its output to $+Vcc$).

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Section 3

1. Modified Colpitts (or Clapp) oscillator

2. Sinewave

3. Common base

4. *C2*, *C3*, *C4* and *L2*

5. 0°

6. Smaller because positive feedback networks introduce a loss.

7. Set up the DC bias conditions for the base of the BJT

8. Couple AC on the BJT's base to common and make the circuit a common base configuration.

9. Couple the output of the oscillator to the next circuit without the DC conditions of either circuit being affected.

10. Isolate the output of the oscillator and power supply line. This prevents RF from escaping onto the power supply line. (It also prevents other components in the circuit affecting the frequency of oscillation.)

11. $fo = \frac{1}{2\pi\sqrt{L_2C_4}}$

    $fo = \frac{1}{2\pi\sqrt{4.5mH \times 2.2nF}}$

    $fo = 50.58kHz$

12. Because they are in series with *C3* and are sufficiently large relative to *C3* not to affect the total capacitance.

13. There is a capacitor in series with the inductor.

14. Make *C4* a variable capacitor.

Section 3 (continued)

15. Hartley oscillator

16. Sinewave

17. Common base

18. *L2*, *L3* and *C4*

19. 0°

20. $fo = \frac{1}{2\pi\sqrt{L_T \times C4}}$

    $fo = \frac{1}{2\pi\sqrt{6mH \times 820pF}}$

    $fo = 71.75kHz$

21. Make *C4* a variable capacitor.

22. Stable output voltage for changes is oscillating frequency.

23. A more pure sinewave (that is, one with less distortion). [That said, the Wien-bridge oscillator is better than both the Hartley and Colpitts oscillators in this regard.]

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Section 4

1. Crystal-controlled Colpitts oscillator

2. Sinewave

3. 550.795kHz

4. Crystal-controlled Hartley oscillator

5. Sinewave

6. 550.795kHz

7. Voltage-controlled oscillator

8. Any two of:

   Function generators
   The implementation of a *phase-locked loop*
   Demodulation of FM radio signals)
   The generation of FM radio signals
   Electronic keyboard/piano
   Analog telemetry

9. Modified Colpitts

10. Varicap diode
    Varactor diode

11. The capacitor's are implemented by the diode's n-type and p-type materials. The plates are separated by a dielectric and this is implemented by the diode's depletion layer at the junction formed where the n-type and p-type materials touch.

12. The size of the depletion layer is affected by the amount of reverse bias the p-n junction experiences. Less reverse bias, thinner depletion layer, so the plates get closer together and the capacitance goes up. More reverse bias, thicker depletion layer, so the plates get further apart and the capacitance goes down.

13. You would measure the DC quiescent conditions on the three terminals of the transistor (that is, V_C, V_B & V_E). This is because the fault is more likely to be in this part of the circuit and by measuring these voltages and applying BJT fault-finding techniques (taught in an earlier subject) you can identify which component is faulty and what's wrong with it.

14. An LCR meter

Section 4 (continued)

15. BJT short-circuit collector-emitter

16. BJT open-circuit collector

17. *R1* open-circuit

18. *R2* high

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Section 5

1. Digital oscillators are a subset of square/rectangular wave oscillators that output waveforms with voltages for the high and low that would be accepted by the input logic device of a given logic family (eg TTL or CMOS) and sub-family (eg 74LS or 74ALS, etc).

2. CMOS crystal-controlled digital oscillator
   Pierce oscillator

3. Digital squarewave

4. 12.038MHz **Note:** This circuit always oscillates at the crystal's fr_2.

5. CMOS

6. 12Vpp

   Note: Importantly, being a digital signal, this will not be a waveform that swings ±6Vp.

7. The balance of probability is the NOT gate is faulty on account of the transistors inside and their small size. The current through the components in the positive feedback network (ie the resistors and the crystal) is so small that it would not significantly degrade their performance in the short or long term.

   Note: In addition to the above, the capacitor is likely to be polyester or ceramic and these are much, much less prone to failure in the first instance than transistors, ICs, etc regardless of how hard they're being made to work. That said, it would be different if the capacitors are electrolytic as these are vulnerable to damage for a number of reasons. However, electrolytic capacitors are unlikely to be used to implement this circuit as their values would ordinarily be too high.

8. Gates with hysteresis don't have a simple ranges of voltages between which the gate's input will be accepted as a logic-0 (eg 0V to 0.8V for TTL), indeterminate (eg > 0.8V and < 2V for TTL and known as the transition zone), or logic-1 (eg 2V to 5V for TTL).

   Instead, they have conditional overlapping voltage ranges implemented using a Schmitt Trigger. So, if an input voltage has been accepted as a logic-0, then it will continue to be accepted as logic-0 for all voltages below, say, 2V and accepted as a logic-1 for 2V and above. But, if an input voltage has been accepted as a logic-1, then it will continue to be accepted as a logic-1 all voltages above, say 0.8V and as a logic-0 for 0.8V and below. Importantly, there is no transition zone.

   [In reality, I wouldn't expect you to answer this question as comprehensively as I have done here. The important things is that you get the concept and having a go at explaining it for yourself helps you to achieve that.]